



CARLO GAVAZZI SPACE SpA

## AMS02 - TCS

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## 1. SCOPE

This document provides the thermal model description and the thermal analysis results of the CAB Thermal Control System (TCS), whose design description is provided in [RD5].

This document corresponds to contract deliverable DEL 070.

## 2. APPLICABLE AND REFERENCE DOCUMENTS

Documents here below identified are applicable and/or reference for the activities described in the present document and are considered part of it to the extent specified herein.

### 2.1 APPLICABLE DOCUMENTS

#### CONTRACTUAL

**AD1** Capitolato generale ASI, available on [http://www.asi.it/html/norme/cap\\_gen.pdf](http://www.asi.it/html/norme/cap_gen.pdf)

**AD2** Richiesta d'offerta per Programma AMS, attività di Fase C/D – Prot. ASI 006194 – 25/07/2007

**AD2bis** CapitolatoTecnico "Progetto: AMS Attività di fase C/D" Doc. N. DC-IPC-2007-062

**AD3** Tailoring di primo livello delle norme ECSS, serie M-E-Q – Progetto AMS attività di fase C/D- Doc. n° DC-IPC-2007-063 Rev. A

#### MANAGEMENT

**AD4** "ECSS Glossary" – Doc. ECSS-P-001 Rev. B

#### PRODUCT ASSURANCE

**AD5** "Product Assurance Requirements - Progetto AMS attività di fase C/D "-Doc. n° DC-IPC-2007-064 Rev. A

**AD6** "Istruzione Operativa "Norme per la redazione del Piano di Assicurazione del Prodotto (PA Plan)", Doc. OP-IPC-2005-008

**AD7** "Sistemi di Gestione per la Qualità", doc. UNI EN ISO 9001:2000

**AD8** "Quality Management Plan for the Alpha Magnetic Spectrometer 02 (AMS-02) Experiment", Doc. JSC63164, Basic Version, 09/21/2005

**AD9** "Master Verification Plan (MVP)", Doc. JSC 29788, Iss. Draft, 8/21/2006

**AD10** "PA REQUIREMENTS DC-IPC-2007-064 RevA Conformity", doc AMSCD-RQ-CGS-001 issue 1

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## ENGINEERING AND TECHNICAL

- AD11 "Multi-Layer Insulation for the Alpha Magnetic Spectrometer Guidelines", Doc. CTSD-SH-1782, 9/30/2005
- AD12 "AMS-02 Structural Verification Plan for the Space Transportation System and the International Space Station", Doc. JSC28792, Iss.D, March 2005
- AD13 "Experiment/Payload Integration Hardware Interfaces - Part I", Doc. JSC29095, Iss.A, 06/01/2002
- AD14 "Experiment/Payload Integration Hardware Interfaces - Part II", Doc. JSC29095, Iss.A, August 2004
- AD15 "Experiment/Vacuum Case Payload Integration Hardware Interface", Doc. JSC29202, Iss.C, March 2005
- AD16 "AMS-02 Thermal Control Requirements", Doc. AMS-RQ-CGS-001, Iss.1, April 2007
- AD17 "Attached Payload Interface Requirements Document", Doc. SSP 57003, Iss. B, 17/06/03
- AD18 "Attached Payload Hardware Interface Control Document, Doc. SSP 57004, Iss. B, 13/06/03
- AD19 "AMSPDS-RP-CGS-001", Doc. PDS Design Description, Iss.2, July 05
- AD20 "AmsE-PPL", AMS Electronics Preferred Parts List, available on (<http://ams.cern.ch/AMS/Electronics/Parts/>), Iss.1, Nov 01 configured on doc PDS-LI-CGS-006 iss 1
- AD23 "CAB TCS Specifications", Doc. AMSTCS-SP-CGS-010, Iss.1, 31/03/2008
- AD24 e-mail from MUÑOZ FERNANDEZ, Guillermo (CRISA), dated 11th February 2008, with ramp up updated power profiles, in closure of actions taken with the AMS collaboration.
- AD25 e-mail from Bollweg, Kenneth (NASA), dated 5th February 2008, in concurrence with the AMS collaboration, stating the environmental conditions for CAB ramp-up.

## 2.2 REFERENCE DOCUMENTS

- [RD 1] Phase II Flight Safety Data Package for the Alpha Magnetic Spectrometer - 02 (AMS-02) Version Basic JSC49978 , 2006
- [RD 2] Alpha Magnetic Spectrometer – 02 Assembly and Testing Integration Plan, Version A, JSC63123, 28-11-2005
- [RD 3] Dichiarazione INFN sulla consegna di componenti – lettera del 20 maggio 2007 (prot. ASI n. 0009869)
- [RD 4] Capitolato gestionale ASI OP-IPC-2005-010-E
- [RD 5] AMSTCS-TN-CGS-010, CAB TCS Design Report, 31/03/2007, issue 1
- [RD 6] AMSTCS-IC-CGS-001, CAB TCS ICD, 31/03/2007, issue 1



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### 3. CAB OPERATING MODES

CAB operative modes for thermal design and analysis cases are defined as follows:

1. CAB Steady modes
  - a. COLD case, in typical dissipation mode and CSP OFF (35 W total dissipation)
  - b. HOT case, in maximum dissipation mode, CSP ON (105W total dissipation)
2. CAB Ramp Up mode in nominal conditions, 6CCS working, 15 minutes stabilization time
3. Switch on sequence, with heaters.
4. Cooling Down

Steady state modes are studied in cyclic orbital conditions, when the thermal balance is reached on all AMS-02 elements.

The RampUp profile is instead a time-defined sequence with a peculiar and non-repetitive power dissipation profile.

The three cases power dissipation is characterized in the following sections:

#### 3.1 STEADY MODES DISSIPATION

The dissipation in the steady state modes is reported in the following tables, where the heat amount is applied on the electronics thermal nodes accordingly. For the model description, see the following sections.

CAB NODE	TYPE	CAB Power dissipation	
		HOT [W]	COLD [W]
101	CAB electronics	1.8	1.63
102	CAB electronics	1.8	1.63
103	CAB electronics	1.8	1.63
104	CAB electronics	1.8	1.63
105	CAB electronics	1.8	1.63
106	CAB electronics	1.8	1.63
107	CAB electronics	8	5.00
108	CAB electronics	17	7.70
109	CAB electronics	9	8.00
110	CAB electronics	3	2.50
111	CAB electronics	3	0.00
112	CAB electronics	9	0.00
113	CAB electronics	3	2.50
114	CAB electronics	3	0.00
115	CAB electronics	7.5	0.00
116	CAB electronics	7.5	0.00
117	CAB electronics	2.5	0.00
118	CAB electronics	11	0.00
119	CAB electronics	11	0.00
TOTAL:		105.3W	35.5W

Tab. 3-1 CAB dissipation in steady state, hot and cold conditions

#### 3.2 RAMP-UP POWER DISSIPATION

In the ramp-up, the power is not constant with time along the CAB nodes.

The total amount of power on the CAB (sum along all the electronics nodes) is reported in the following figure , as specified in [AD24].



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Ramp-up total power (6 CCS)

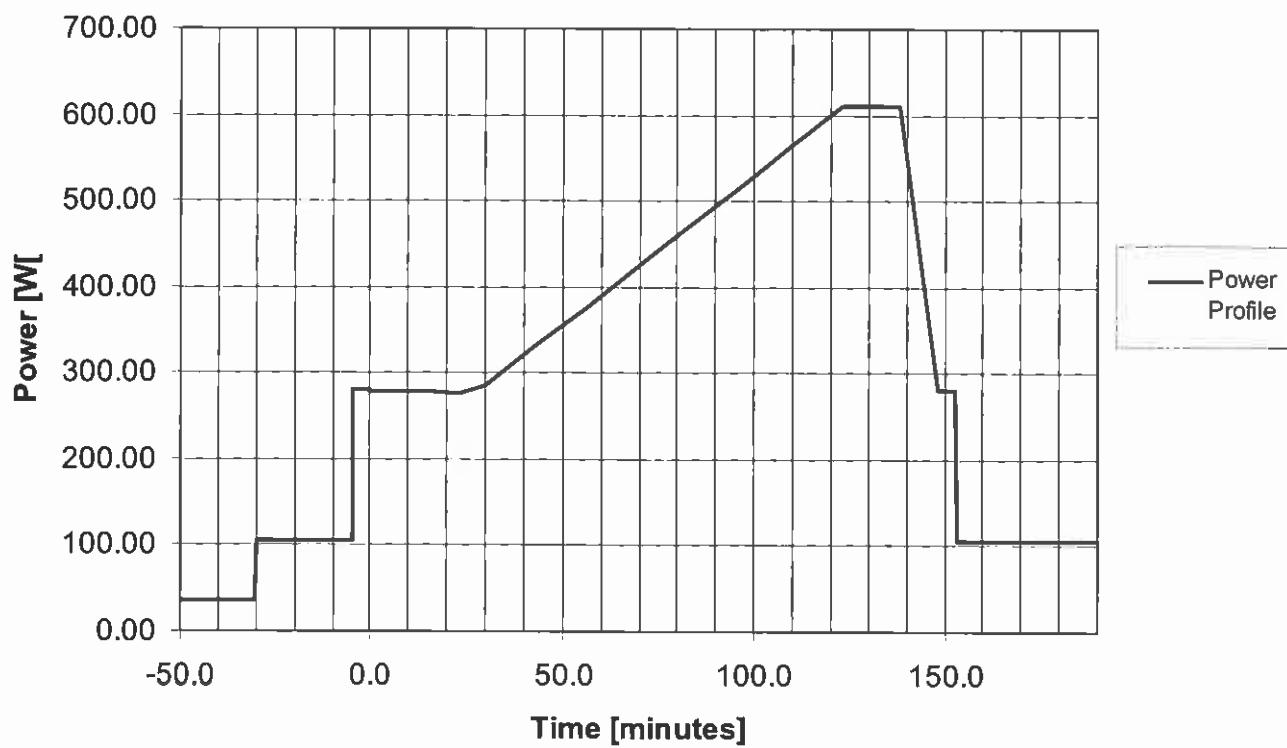


Fig. 3-1 CAB cumulative power profile during ramp up

The Ramp-up is implemented in the analysis as follows:

- Phase 1: hot case stabilization, with 105W (max power dissipation in steady state)  
Phase 2: cooling down case, with 35W power dissipation (minimum value) for 5 orbits (about 7 hours)  
Phase 3: ramp up profile implementation, where
- 3a the power increases from 35 to 105W (transition located at time -30 minutes in the figure above)
  - 3b then follows the profile of the ramp (about 25 minutes at 105W)
  - 3c then about 30 minutes at 270W,
  - 3d then the slope until about 610W are dissipated (about 100 minutes)
  - 3e 15 minutes at maximum and stable dissipation level
  - 3f power decreases to the maximum nominal steady state dissipation, 105W, in about 15 minutes

### 3.3 SWITCH ON POWER DISSIPATION

In the switch on phase, the CAB is in OFF mode and the heaters power (100W @113VDC, see CAB design description) are used to bring the unit up to its minimum switch on temperature. Power application is on the relevant CAB walls nodes, according to the layout and position of the heater patches.



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## 4. CAB TEMPERATURE REQUIREMENTS

CAB temperature requirements are set along two CAB walls, the Starboard and the Wake facing sides. Temperature limits are defined in AD 16 and AD23, and are reported below for sake of clarity.

Wake face nodes are numbered 301 to 319, Starboard face nodes are numbered 201 to 219 in the thermal model and in the tables below.

The Non operational temperatures (continuous)on these faces are -30°C +70°C for all the nodes during non-operational scenarios heater supported.

The non-operational temperatures for short period of time, e.g. power outage , are -40°C  
The minimum switch on temperature is -25°C on all these nodes.

The operational temperatures are different according to the steady or ramp up case under study

### 4.1 STEADY STATE TEMPERATURE REQUIREMENTS

Node	Module	Min °C	Max °C	Node	Module	Min °C	Max °C
301	CCS CS 1	-25	45	201	CCS CS 1	-25	44
302	CCS CS 2	-25	45	202	CCS CS 2	-25	44
303	CCS CS 3	-25	44	203	CCS CS 3	-25	43
304	CCS CS 4	-25	44	204	CCS CS 4	-25	41
305	CCS CS 5	-25	44	205	CCS CS 5	-25	40
306	CCS CS 6	-25	44	206	CCS CS 6	-25	40
307	CCS CTRL TMTC	-25	45	207	CCS CTRL TMTC	-25	40
308	28V ISO	-25	45	208	28V ISO	-25	40
309	CCSC STM (Nom)	-25	46	209	CCSC STM (Nom)	-25	41
310	PTM (Nom)	-25	46	210	PTM (Nom)	-25	44
311	PTM (Red)	-25	46	211	PTM (Red)	-25	47
312	CCSC STM (Red)	-25	47	212	CCSC STM (Red)	-25	48
313	PS (Nom)	-25	47	213	PS (Nom)	-25	49
314	PS (Red)	-25	46	214	PS (Red)	-25	50
315	CSP PWR DRV (Nom)	-25	46	215	CSP PWR DRV (Nom)	-25	50
316	CSP PWR DRV (Red)	-25	46	216	CSP PWR DRV (Red)	-25	50
317	CSP TM/TC (Nom / Red)	-25	46	217	CSP TM/TC (Nom / Red)	-25	50
318	CSP CL DET & CV	-25	46	218	CSP CL DET & CV	-25	51
319	CSP MAG DET & CV	-25	46	219	CSP MAG DET & CV	-25	51

Tab. 4-1 CAB temperature requirements (wall nodes) in steady operational mode

### 4.2 RAMP UP TEMPERATURE REQUIREMENTS

Node	Module	Min °C	Max °C	Node	Module	Min °C	Max °C
301	CCS CS 1	-25	57	201	CCS CS 1	-25	61
302	CCS CS 2	-25	56	202	CCS CS 2	-25	61
303	CCS CS 3	-25	55	203	CCS CS 3	-25	58
304	CCS CS 4	-25	54	204	CCS CS 4	-25	49
305	CCS CS 5	-25	54	205	CCS CS 5	-25	46



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Node	Module	Min °C	Max °C	Node	Module	Min °C	Max °C
306	CCS CS 6	-25	53	206	CCS CS 6	-25	45
307	CCS CTRL TMTC	-25	51	207	CCS CTRL TMTC	-25	41
308	28V ISO	-25	50	208	28V ISO	-25	39
309	CCSC STM (Nom)	-25	50	209	CCSC STM (Nom)	-25	40
310	PTM (Nom)	-25	50	210	PTM (Nom)	-25	44
311	PTM (Red)	-25	50	211	PTM (Red)	-25	47
312	CCSC STM (Red)	-25	50	212	CCSC STM (Red)	-25	49
313	PS (Nom)	-25	50	213	PS (Nom)	-25	50
314	PS (Red)	-25	50	214	PS (Red)	-25	50
315	CSP PWR DRV (Nom)	-25	51	215	CSP PWR DRV (Nom)	-25	51
316	CSP PWR DRV (Red)	-25	51	216	CSP PWR DRV (Red)	-25	51
317	CSP TM/TC (Nom / Red)	-25	50	217	CSP TM/TC (Nom / Red)	-25	51
318	CSP CL DET & CV	-25	51	218	CSP CL DET & CV	-25	52
319	CSP MAG DET & CV	-25	51	219	CSP MAG DET & CV	-25	52

Tab. 4-2 CAB temperature requirements (wall nodes) in ramp-up operational mode



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## 5. ENVIRONMENTAL CASES AND CONFIGURATION

The environmental cases for the dimensioning and the performance check of the CAB TCS are recalled in the following sections.

Apart from the Ramp-up case, the orbital parameters have been selected according to the survey based on 4.2 AMS system thermal model on all the possible combinations of attitudes and beta angles onboard of the ISS.

According to the HOT and COLD cases, the environmental conditions consider the worst combination of

- Solar Constant (1322 to 1424 W/m<sup>2</sup>)
- Earth IR emission temperature (245.5 to 266.5 K)
- Albedo value (0.2 to 0.4)

Model description is given in section 6.

### 5.1 WORST HOT STEADY CASES

Environmental case	worst HOT
Beta angle	-75°
Attitude (Yaw/Pitch/Roll)	-15°, 25°, 15°
Optical properties	EOL
Model type	System
System Model reference	4.2
Model remarks	debris shield included

Tab. 5-1 Worst hot steady case parameters

This case represents the worst hot environmental and orbital conditions (beta angle and attitude) combination.

Environmental case	typical HOT
Beta angle	-75°
Attitude (Yaw/Pitch/Roll)	0°, 0°, 0°
Optical properties	EOL
Model type	system
System Model reference	4.2
Model remarks	debris shield included

Tab. 5-2 Typical hot steady case parameters

This case has the same beta angle proper of the worst hot case, but a relaxation is introduced on the attitude, which is taken as the typical attitude the ISS will adopt during flight.

**The abovementioned cases are to be considered only for the Hot case-steady state dissipation (not applicable to ramp up)**



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## 5.2 WORST COLD STEADY CASES &amp; SWITCH ON

Environmental case	worst COLD
Beta angle	75°
Attitude (Yaw/Pitch/Roll)	-15°,-20°,15°
Optical properties	BOL
Model type	system
System Model reference	4.2
Model remarks	debris shield included

Tab. 5-3 Worst cold steady case parameters

This case represents the worst cold environmental and orbital conditions (beta angle and attitude) combination. This case is used for switch on heater sizing and cold steady state operative modes analysis, and for the cooling down analysis (see sections 7.4 and 7.5 ).

## 5.3 RAMP UP

Environmental case	hot, not extreme
Beta angle	-50°
Attitude (Yaw/Pitch/Roll)	0°,0°,0°
Optical properties	EOL
Model type	2-phase
System Model reference	4.2
Model remarks	debris shield included at 2-phase level

Tab. 5-4 Hot dimensioning case parameters for ramp up

This case represents the combination of the worst hot environmental conditions with a less demanding beta angle and attitude profile. This is because the very demanding power dissipation of the ramp-up cannot be superimposed to the worst hot conditions.

Due to the CAB location on the AMS (and with respect to the ISS), the worst cases occur when the beta angle takes large negative values, close to the minimum possible value -75°. Thermal environment is less demanding as soon as higher beta angles values are attained.

Being the evolution of the beta angle deterministic, it is possible to evaluate:

1. the maximum duration of the period in which the beta angle is lower than the given value
2. the fraction of the total time spent by the ISS below this beta angle
3. the time distribution of these periods along the year.



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Beta angle

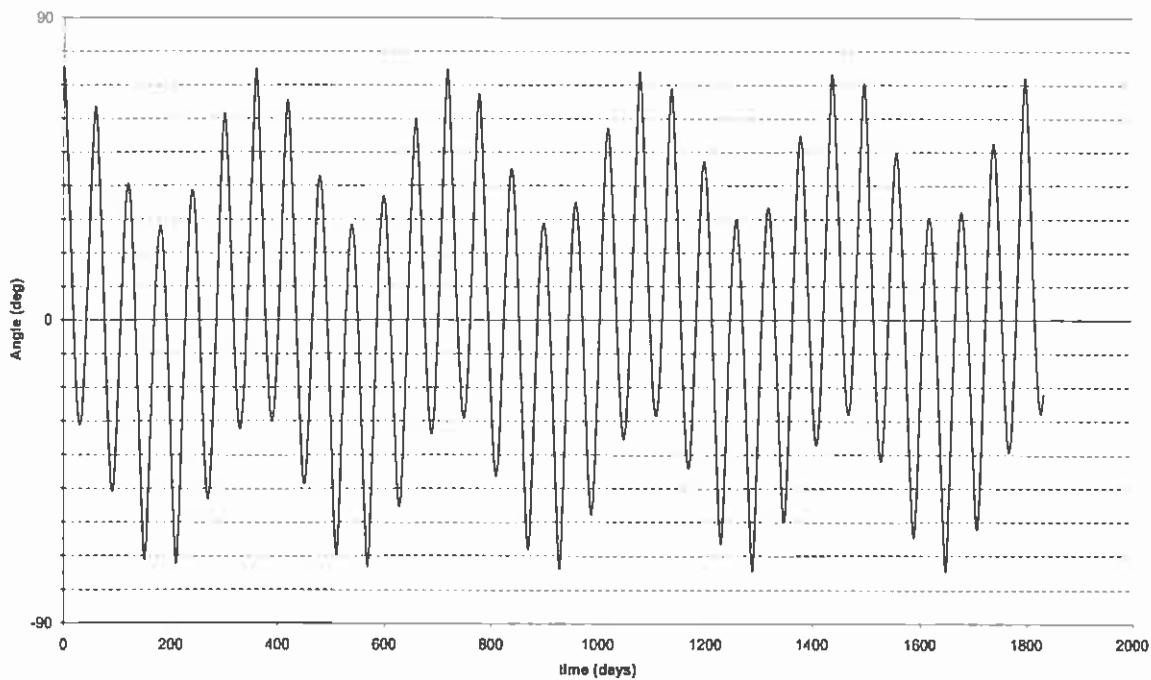
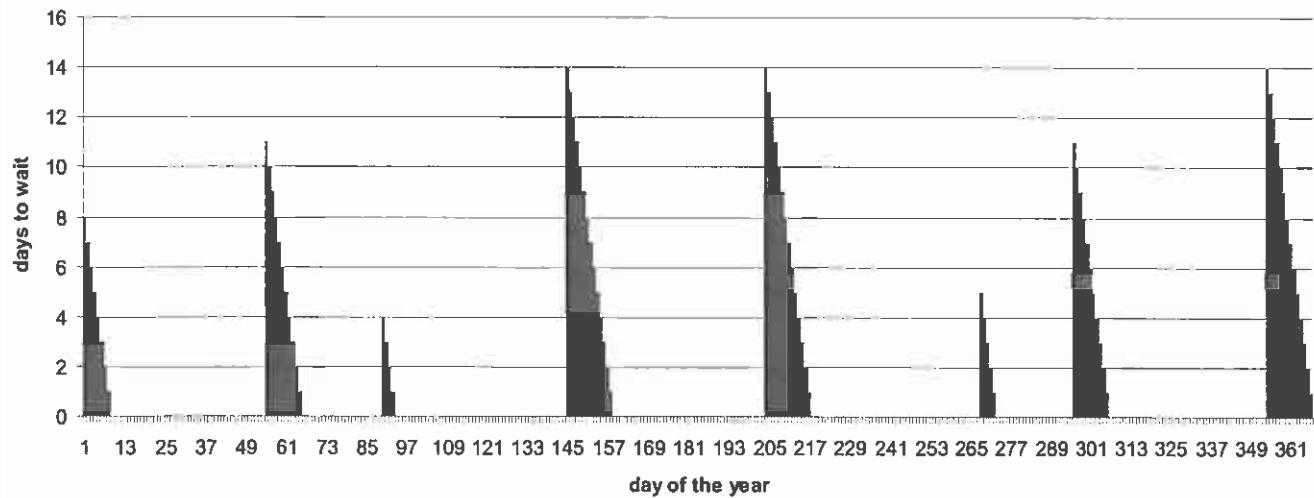


Fig. 5-1 ISS beta angle time evolution

Number of days to wait before returning within beta  $\pm 50^\circ$ Fig. 5-2 number of days to wait before the beta angle becomes lower than  $50^\circ$  in modulus; null value means that beta angle is already between  $+50^\circ$  and  $-50^\circ$ 

It comes out that the longest "forbidden" period is 14 days. The fraction of the time spent at beta angles higher than  $50^\circ$  in modulus is 20 % of the mission time. This situations happen 8 times per year in average.

These orbital restrictions for the ramp-up case have been considered acceptable by the AMS collaboration (see AD25).



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## 6. MODELS DESCRIPTION

There are 3 thermal models which have been developed to predict the thermal behaviour of the CAB:

- The CAB detailed thermal model, developed by CRISA
- The CAB reduced thermal model, inserted in the AMS system level model (maintained by CGS)
- The CAB TCS 2-phase model, developed in ECOSIMPRO on the basis of the input data and interfaces provided by the system level model, developed by Iberespacio

The models communicate in according to the following scheme:

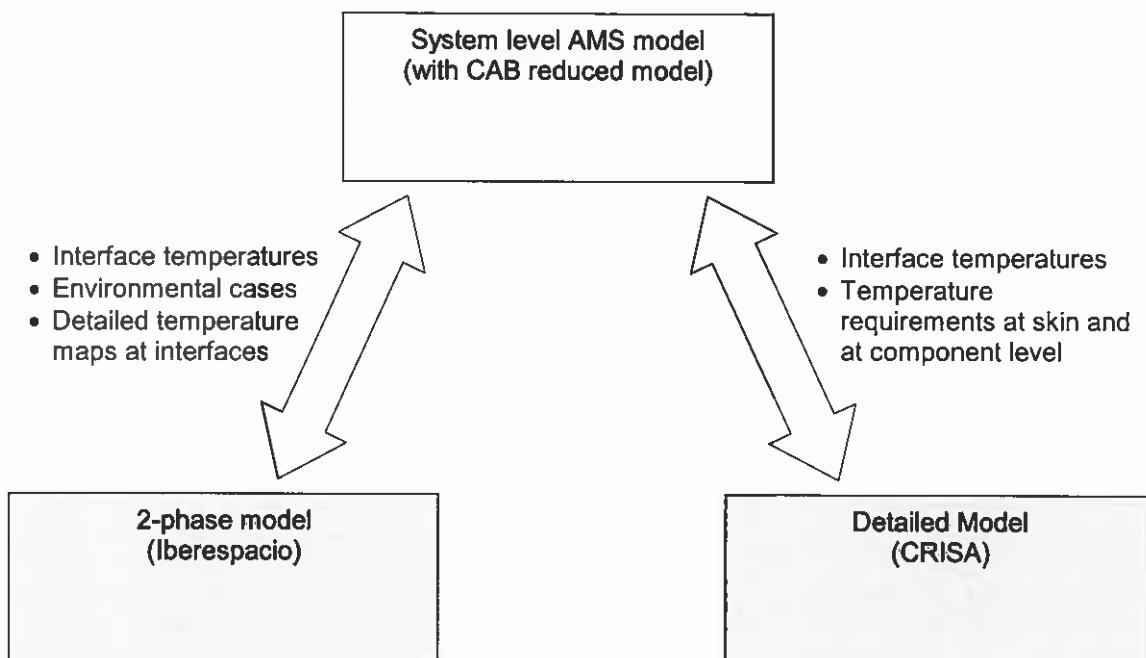


Fig. 6-1 (CAB) Model interactions

The System level model communicates separately with both detailed CAB model and with the 2-phase model. The system level model includes the reduced model of all the AMS subsystems, and the ISS, and is therefore able to manage all the mutual interactions among them, and the external environmental and orbital conditions.

The system level model provides temperature maps at the interfaces to the detailed CAB CRISA model in an iterative process. The detailed model is then run, with a much higher level of detail, to verify temperature at component level (which are missing in the system CAB reduced model). The result of the iterations is the provision of temperature maps at the interfaces, which lead to the fulfilment of the requirements at component level. These temperature maps are finally taken as temperature requirements for the CAB, which can be easily verified with the reduced model.

The system level model communicates also with the 2-phase model. The 2-phase model can be considered as a simplified subset of the system level model, which includes only the relevant CAB TCS elements only, plus the addition of the detailed model of the fluidic components (LHP). The environment seen by the 2-phase model (which accounts for the other subdetectors and for the ISS) is generated by the system level model and is included in the 2-phase model by the application of the interface data (equivalent sink temperatures, orbital fluxes, radiative couplings, boundary conditions). The 2-phase model manages the complex LHP system, properly accounting the



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heat transfer phenomenon by the phase change vapour-liquid. The 2-phase model is therefore needed for the LHP system dimensioning, and for detailed predictions under critical conditions (e.g., the ramp-up process).

This document covers the results obtained with the system level model and the 2-phase model (built under CGS responsibility), and verifies the requirements fulfilment at the CAB external walls as previously defined after the iterations with the detailed CAB model.

The system and the 2-phase model are recalled in the following sections. These models have been built on the basis of the TCS design described in [RD5].

## 6.1 SYSTEM MODEL DESCRIPTION (CAB SECTION)

### 6.1.1 GEOMETRICAL MATHEMATICAL MODEL

A Geometric Mathematical Model has been developed to calculate the outer radiative coupling among the different surfaces of the CAB and between the CAB and the external environment (including AMS-02 and ISS elements).

The following images show the geometric models o the relevant parts:



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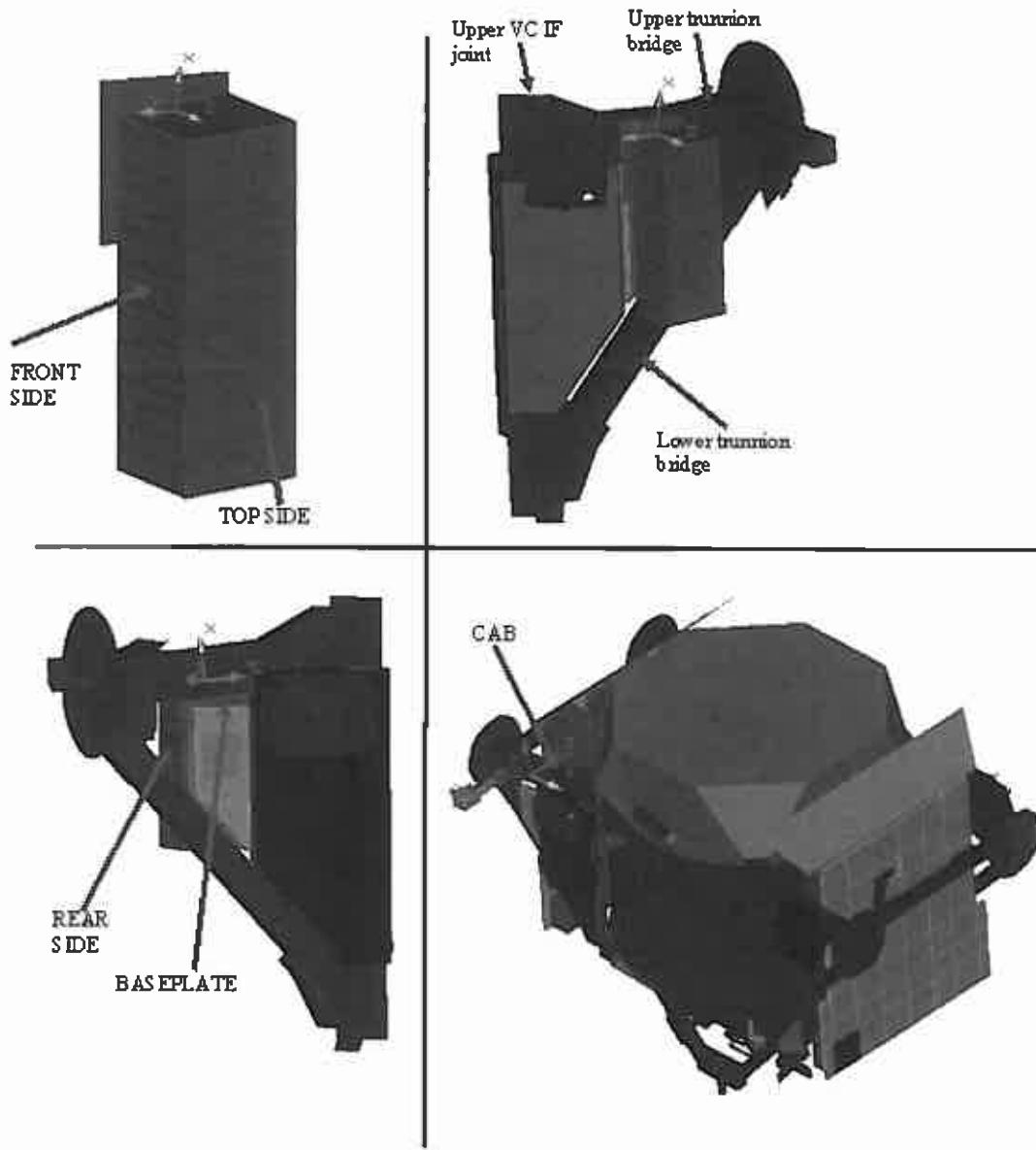


Fig. 6-2Views of the CAB GMM

In the last figure CAB is hidden by the debris shield.

The thermo-optical properties used are shown in the following pictures:



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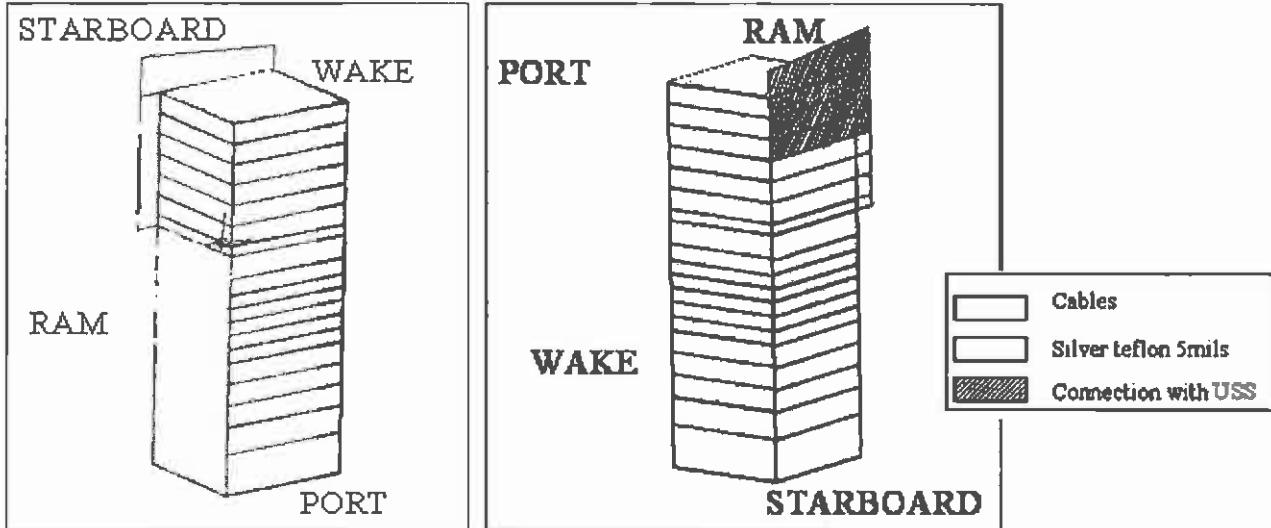
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Fig. 6-3 CAB thermo-optical properties

The values used are shown in the following table:

	BOL		EOL	
	$\epsilon$	$\alpha$	$\epsilon$	$\alpha$
Beta cloth/cables	0.9	0.22	0.86	0.47
Silver Teflon 5mils	0.78	0.08	0.75	0.13

Tab. 6-1 CAB thermo-optical properties

In order to be conservative the BOL properties are used for cold analysis while the EOL are used for hot analysis. Cables are modelled considering radiative links with the environment; the external optical property is beta cloth, as for MLI.

### 6.1.2 THERMAL MATHEMATICAL MODEL

Since the number of nodes in the detailed model is very high, the model delivered to the system has been reduced (RTMM and RGMM has been used for:

- IF data generation at system level for detailed analysis performed at subsystem level
- Flight temperature prediction at system level
- Test temperature predictions at system level

The reduced model must be representative of the detailed one from which it is issued in term of:

1. I/F temperatures
2. Evolution of the temperature along the time
3. Distribution of the thermal fluxes at the I/F (both conductive and radiative)

The representativity acceptance criteria are the following one:

1. maximum 3°C for I/F temperatures
2. same time constant
3. Heat exchange budget: within 10%

#### 6.1.2.1 NODAL BREAKDOWN

In SINDA code there is not a division in thermal submodels. We are considering only one submodel called CAB.



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CAB nodes are listed in the following table, with their thermal capacitance.

Node number	Description	Thermal Capacitance J/K
200		577.6
201÷206		365.7
207		191.1
208		247.9
209		101.7
210÷211	Baseplate (-X)	80.1
212÷214		85.7
215÷216		131.8
217		134.4
218		167.2
219		251.6
301÷306		146.3
307		76.4
308		164.4
309		117.9
310÷311	WAKE (+Y)	93.1
312÷314		99.7
315÷316		152.8
317		155.7
318		194.3
319		291.8
401÷406		43.4
407		22.7
408		48.8
409		35.0
410÷411	RAM (-Y)	27.6
412÷414		29.6
415÷416		45.4
417		46.2
418		57.7
419		86.6
501÷506		173.4
507		90.7
508		194.6
509		139.8
510÷511	Top (+X)	110.0
512÷514		117.8
515÷516		181.1
517		184.6
518		229.7
519		345.6



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Node number	Description	Thermal Capacitance J/K
10	External wires	965.2
20	Current shunt	2117.9
101÷106	CCS CS	1890
107	CCS CTRL TMTC	1080
108	28V ISO	1530
109÷114	CCSC STN PMT OS	1035
115÷116	CSP PWR DRV	1080
117	CSP TM/TC	990
118	CSO CK DET & CV	1620
119	CSO NAG DET & CV	1530
601	Zenith	321.2
602	Nadir	321.2
1501÷1519	Junction nodes	-
1701÷1719		-

Fig. 6-4 CAB numbering

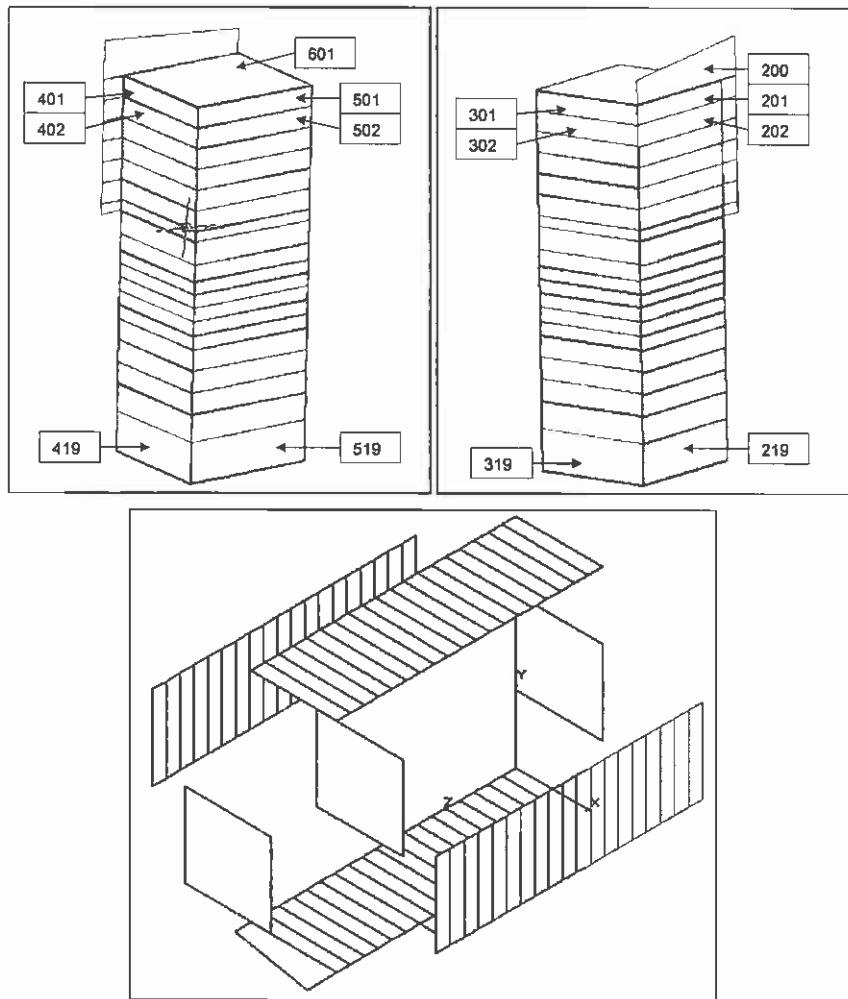


Fig. 6-5 CAB nodal breakdown



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The reduced model has the dissipation power concentrated in one node for each electronic board. This node temperature is not always correlated with the average temperature of the module.

### 6.1.2.2 LINEAR CONDUCTORS

The conductors between different nodes are summarized in the following tables:

Conductors between electronic nodes and skin nodes				
Node 1	Description	Node 2	Description	Linear Conductor [W/K]
101	electronics	201	baseplate	1.02
102		202		1.02
103		203		1.02
104		204		1.02
105		205		1.02
106		206		1.02
107		207		0.11
108		208		0.23
109		209		0.13
110		210		0.12
111		211		0.12
112		212		0.13
113		213		0.13
114		214		0.13
115		215		0.16
116		216		0.16
117		217		0.13
118		218		0.16
119		219		0.16
101	electronics	301	WAKE side	0.09
102		302		0.09
103		303		0.09
104		304		0.09
105		305		0.09
106		306		0.09
107		307		0.05
108		308		0.10
109		309		0.06
110		310		0.06
111		311		0.06
112		312		0.06
113		313		0.06
114		314		0.06
115		315		0.07
116		316		0.07
117		317		0.06
118		318		0.31
119		319		0.31



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Conductors between electronic nodes and skin nodes				
Node 1	Description	Node 2	Description	Linear Conductor [W/K]
101	electronics	401	RAM side	0.05
102		402		0.05
103		403		0.05
104		404		0.05
105		405		0.05
106		406		0.05
107		407		0.03
108		408		0.05
109		409		0.03
110		410		0.03
111		411		0.03
112		412		0.03
113		413		0.03
114		414		0.03
115		415		0.04
116		416		0.04
117		417		0.03
118		418		0.004
119		419		0.004
101	electronics	501	Top side	0.15
102		502		0.15
103		503		0.15
104		504		0.15
105		505		0.15
106		506		0.15
107		507		0.1
108		508		0.2
109		509		0.11
110		510		0.11
111		511		0.11
112		512		0.11
113		513		0.11
114		514		0.11
115		515		0.14
116		516		0.14
117		517		0.11
118		518		0.15
119		519		0.15

Fig. 6-6 Linear conductors between electronic nodes and skin nodes (reduced model)



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Conductors between skin nodes				
Node 1	Description	Node 2	Description	Linear Conductor [W/K]
200	baseplate	201	baseplate	6.8
201		202		8.8
202		203		8.8
203		204		8.8
204		205		8.8
205		206		8.8
206		207		11.5
207		208		9.9
208		209		2.35
209		210		3.14
210		211		3.58
211		212		3.45
212		213		3.34
213		214		3.34
214		215		2.64
215		216		2.18
216		217		2.16
217		218		1.90
218		219		1.37
301	WAKE side	302	WAKE side	1.77
302		303		1.77
303		304		1.77
304		305		1.77
305		306		1.77
306		307		2.33
307		308		2.17
308		309		1.83
309		310		2.47
310		311		2.80
311		312		2.71
312		313		2.62
313		314		2.62
314		315		2.06
315		316		1.70
316		317		1.68
317		318		1.49
318		319		1.07



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Conductors between skin nodes				
Node 1	Description	Node 2	Description	Linear Conductor [W/K]
401	RAM side	402	RAM side	1.77
402		403		1.77
403		404		1.77
404		405		1.77
405		406		1.77
406		407		2.33
407		408		2.17
408		409		1.83
409		410		2.47
410		411		2.8
411		412		2.71
412		413		2.62
413		414		2.62
414		415		2.06
415		416		1.7
416		417		1.68
417		418		1.49
418		419		1.07
501	Top side	502	Top side	2.67
502		503		2.67
503		504		2.67
504		505		2.67
505		506		2.67
506		507		3.50
507		508		3.23
508		509		2.76
509		510		3.69
510		511		4.20
511		512		4.06
512		513		3.92
513		514		3.92
514		515		3.1
515		516		2.56
516		517		2.53
517		518		2.24
518		519		1.60



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Conductors between skin nodes				
Node 1	Description	Node 2	Description	Linear Conductor [W/K]
201	baseplate	401	RAM side	0.08
202		402		0.08
203		403		0.08
204		404		0.08
205		405		0.08
206		406		0.08
207		407		0.04
208		408		0.09
209		409		0.06
210		410		0.05
211		411		0.05
212		412		0.05
213		413		0.05
214		414		0.05
215		415		0.08
216		416		0.08
217		417		0.08
218		418		0.1
219		419		0.16
401	RAM side	501	Top side	0.08
402		502		0.08
403		503		0.08
404		504		0.08
405		505		0.08
406		506		0.08
407		507		0.04
408		508		0.09
409		509		0.06
410		510		0.05
411		511		0.05
412		512		0.05
413		513		0.05
414		514		0.05
415		515		0.08
416		516		0.08
417		517		0.08
418		518		0.10
419		519		0.16
601	Zenith	201	Baseplate	0.48
601		301	WAKE side	0.44
601		401	RAM side	0.44
601		501	Top side	0.46
602	Nadir	219	Baseplate	0.42
602		319	WAKE side	0.39
602		419	RAM side	0.39
602		519	Top side	0.42



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The WAKE side nodes are not directly connected with the base-plate and the top side nodes. They are connected with the junction nodes, and then the junction nodes are connected with the baseplate and the top side.

Conductors between skin nodes				
Node 1	Description	Node 2	Description	Linear Conductor [W/K]
301	WAKE side	1501	Junction nodes	0.08
302		1502		0.08
303		1503		0.08
304		1504		0.08
305		1505		0.08
306		1506		0.08
307		1507		0.04
308		1508		0.09
309		1509		0.06
310		1510		0.05
311		1511		0.05
312		1512		0.05
313		1513		0.05
314		1514		0.05
315		1515		0.08
316		1516		0.08
317		1517		0.08
318		1518		0.1
301	WAKE side	1701	Junction nodes	0.08
302		1702		0.08
303		1703		0.08
304		1704		0.08
305		1705		0.08
306		1706		0.08
307		1707		0.04
308		1708		0.09
309		1709		0.06
310		1710		0.05
311		1711		0.05
312		1712		0.05
313		1713		0.05
314		1714		0.05
315		1715		0.08
316		1716		0.08
317		1717		0.08
318		1718		0.1



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Conductors between skin nodes				
Node 1	Description	Node 2	Description	Linear Conductor [W/K]
501	Top side	1501	Junction nodes	0.38
502		1502		0.42
503		1503		0.47
504		1504		0.52
505		1505		0.56
506		1506		0.61
507		1507		0.34
508		1508		0.79
509		1509		0.61
510		1510		0.51
511		1511		0.54
512		1512		0.61
513		1513		0.64
514		1514		0.67
515		1515		1.08
516		1516		1.13
517		1517		1.20
518		1518		1.56
201	Baseplate	1701	Junction nodes	0.38
202		1702		0.38
203		1703		0.38
204		1704		0.38
205		1705		0.38
206		1706		0.38
207		1707		0.2
208		1708		0.42
209		1709		0.30
210		1710		0.24
211		1711		0.24
212		1712		0.25
213		1713		0.25
214		1714		0.25
215		1715		0.39
216		1716		0.39
217		1717		0.4
218		1718		0.5

Fig. 6-7 Linear conductors between skin nodes (reduced model)



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The conductors between CAB and USS02 are shown in the following table:

Conductors between CAB baseplate and USS02				
Node 1	Description	Node 2	Description	Linear Conductor [W/K]
200	baseplate	20213	USS02 Upper Trunnion Bridge	2.05
200		20217		0.0129
200		20221		2.20E-03
200		20212		1.50E-03
201		20212		1.20E-03
200		20216		2.40E-03
201		20216		7.30E-03
201		20220		2.20E-03
201		20211		1.40E-03
202		20211		1.20E-03
201		20215		4.90E-03
202		20215		7.30E-03
202		20219		2.20E-03
202		20210		1.40E-03
203		20210		1.20E-03
202		20214		4.90E-03
203		20214		7.30E-03
203		20218		2.20E-03

Tab. 6-2 Conductors between CAB baseplate and USS02 Upper Trunnion Bridge

The conductors between CAB and LHP saddle are shown in the following table:

Conductors between CAB baseplate and USS02				
Node 1	Description	Node 2	Description	Linear Conductor [W/K]
204	baseplate	1	LHP 1 saddle	4.5
205				4.5
206				4.5
207				2.3
208				5.2
209				3.0
204	baseplate	2	LHP 2 saddle	4.5
205				4.5
206				4.5
207				2.3
208				5.2
209				3.0

Tab. 6-3 Conductors between CAB baseplate and LHP saddles

The conductors between CAB and HPs mounted on WAKE and Top side are shown in the following table:

Conductors between CAB baseplate and USS02				
Node 1	Description	Node 2	Description	Linear Conductor [W/K]
301	WAKE side	701	Hp mounted on WAKE side	1.426
302				1.426
303				1.426



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304				1.426
305				1.426
306				1.426
307				0.721
308				1.616
309				0.952
310				0.952
311				0.799
312				0.952
313				0.952
314				0.952
315				1.426
316				1.426
317				1.426
318				1.747
319				2.721
501				1.426
502				1.426
503				1.426
504				1.426
505				1.426
506				1.426
507				0.721
508				1.616
509				0.952
510				0.952
511				0.799
512				0.952
513				0.952
514				0.952
515				1.426
516				1.426
517				1.426
518				1.747
519				2.721

Tab. 6-4 Conductors between CAB baseplate and LHP saddles



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## 6.1.2.3 RADIATIVE CONDUCTORS

The internal radiative links, provided directly by CRISA, are summarized in the following table:

Conductors between skin nodes				
Node 1	Description	Node 2	Description	Radiative Conductor [W/K]
101		102		2.52E-09
102		103		2.52E-09
103		104		2.52E-09
104		105		2.52E-09
105		106		2.52E-09
106		107		5.46E-10
107		108		5.46E-10
108		109		5.46E-10
109		110		5.46E-10
110		111		2.52E-09
111		112		5.46E-10
112		113		2.52E-09
113		114		2.52E-09
114		115		2.52E-09
115		116		2.52E-09
116		117		2.52E-09
117		118		2.52E-09
118		119		5.46E-10
101	electronic	601	Zenith	5.46E-10
119		602	Nadir	5.46E-10

Fig. 6-8 Radiative conductors (reduced model)

They have been calculated considering the PCBs treated with silicone coating ( $\epsilon=0.8$ ), the aluminum parts are treated with alodine ( $\epsilon=0.15$ ) and the view factors considered between PCBs and CAB lateral walls is equal to 1, since they are very close parallel planes. Multiple reflection between them is taken into account.

## 6.1.2.4 CONTACT CONDUCTANCES

In the thermal model the following contact conductance have been used:

- 500 W/m<sup>2</sup>/K between baseplate and Upper Trunnion Bridge
- 1200 W/m<sup>2</sup>/K between HP flanges and CAB walls
- 1000 W/m<sup>2</sup>/K between LHP evaporator and CAB baseplate
- 800 W/m<sup>2</sup>/K between LHP condenser and WAKE radiator radiative side
- 1200 W/m<sup>2</sup>/K between HP and WAKE radiator radiative side

## 6.2 2-PHASE MODEL DESCRIPTION

The 2-phase model is composed of a subsection of the system model and by the LHP fluidic model. The system model subsection description and modelling approach is described in the following section.

### 6.2.1 THERMAL CONTROL SYSTEM OVERVIEW

CAB internally generated power, and external incoming fluxes, are sunk to three main items:

1. Space (or radiative environment)
2. USS (the mechanical support structure for the CAB)
3. the Wake Radiator, through the LHP. On its turn, the radiator is sunk to its environment.

The thermal network of these items (with exception of the LHP) is built by CGS.

CGS shall provide all nodes definitions, conductor definitions, and heat loads definitions.

IE shall insert the LHP model, shall properly model the heat transport capabilities of the LHP, and shall derive the temperature profiles on the basis of the environmental data (boundary temperatures and fluxes) provided by CGS.

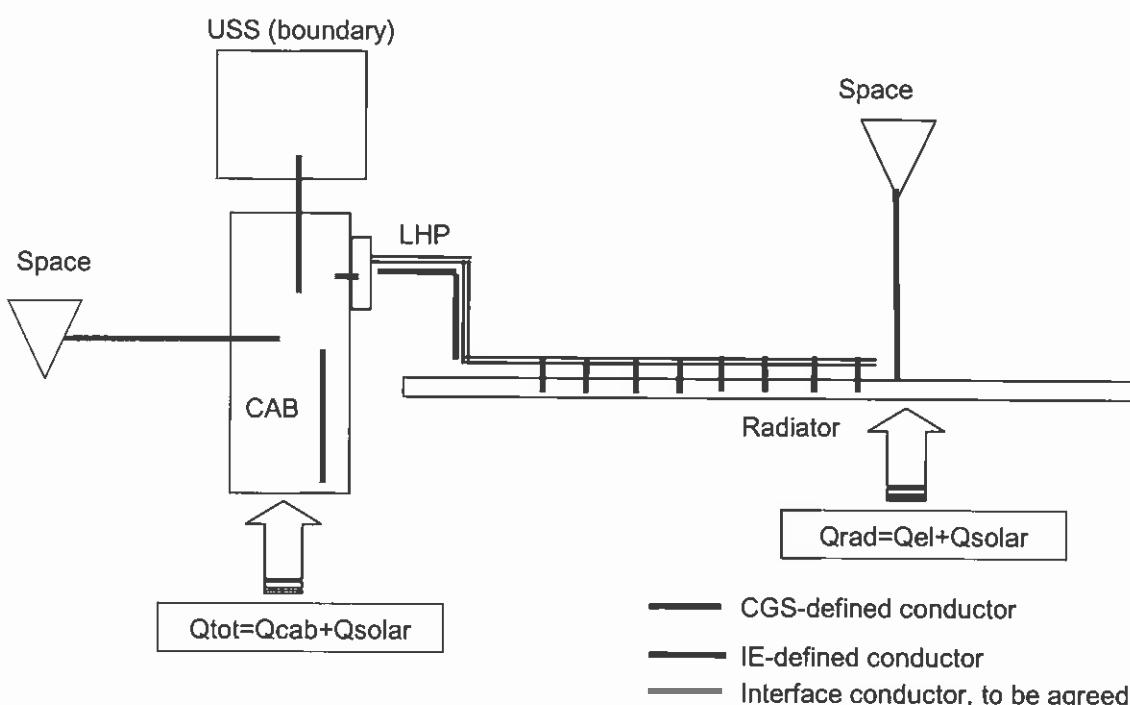


Fig. 6-9 CAB reduced model interfaces and structure

### 6.2.2 THERMAL MODEL DESCRIPTION

Thermal model data shall be delivered in two different sets:

1. The first batch of model data serves for the building-up of the thermal network. Therefore, in the first set the nodes definitions are given, the conductors and the power sources. This set defines the topology of the network.
2. A second set of information of the model is given with the INTERFACE (I/F) DATA. These data are dependent on the specific case under study. These data include power sources, variable radiative couplings, boundary temperatures.

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In the following sections, the topology is described.

### 6.2.2.1 NODES

The CAB+Wake radiator (RAD) thermal network is composed of the following node families:

- diffusive nodes
  - CAB nodes 91 in total
  - Radiator nodes 149 in total
- boundary nodes (environment)
  - CAB environmental nodes 39 in total
  - USS nodes 1 node
  - RAD environmental nodes. 94 in total

With respect to the system reduced model, the following further simplifications have been made in order to decrease the total model weight (due to ECOSIMPRO limitations):

1. CAB diffusive nodes are condensed from series x12 to x19; in fact, the CAB model is modular, with a "slice" in correspondence of each board. Each slice has 4 mechanical walls nodes, plus 3 internal electronics nodes. Since the series x12 to x19 are distant from the interfaces with the LHOP and with the USS, they can be safely condensed without affecting 2-phase model results.
2. Radiator diffusive nodes were strongly reduced: only skin nodes were kept, all HP nodes were condensed to one node per HP, rohacell nodes were deleted and the conductors only were kept.
3. CAB environmental nodes were carefully checked, and whenever a set of environmental nodes of adjacent CAB nodes was similar within 5°C, it was condensed into a unique environmental node.
4. USS interface nodes were reduced from 9 to 1 interface node, taking the average temperature (all temperatures were within 2°C).
5. RAD environmental nodes were averaged whenever the MERAT was within 10°C among adjacent nodes.

### 6.2.2.2 CONDUCTORS

Conductors were reduced according to the nodalization reported in the previous paragraph.

The total number of linear and radiative conductors (mainly from diffusive nodes to the environmental boundary nodes) are.

- 467 inter-radiator linear conductors
- 221 inter-CAB linear conductors
- 4 CAB-USS linear conductors
- 122 radiator to environment radiative conductors
- 63 CAB to environment radiative conductors

### 6.2.2.3 SOURCES

The sources are of 2 kinds:

1. Electronic dissipation sources, inside the CAB and on the Radiator; these sources are:
  - a. Constant, in the worst hot and worst cold orbital operational scenarios
  - b. According to a specified profile, for the ramp-up scenario.
2. External fluxes, on the CAB and RAD surfaces. These fluxes are typically time-dependent

Some nodes can have BOTH an electronics power consumption (constant value) AND an external flux. In these cases, the power must be summed in the thermal model.



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### 6.2.3 THERMAL INTERFACES CGS-IE

The CGS thermal model is interfacing the IE model at 2 locations: the evaporator and the condenser zone. A detailed description is provided in the following sections.

#### 6.2.3.1 EVAPORATOR INTERFACE

The exact position and size/shape of the evaporator is up to IE design and engineering judgement.

The following constraints apply (from the specification requirements):

- The hole pattern on the CAB is already established (highlighted in red in the following figure)
- The stay-in area of the evaporator zone has been provided
- As a design driver, the evaporator should be placed at the "highest" position, as close as possible to the USS (but within stay-in volume).

Please note that NOT ALL holes on the CAB must be necessarily used.

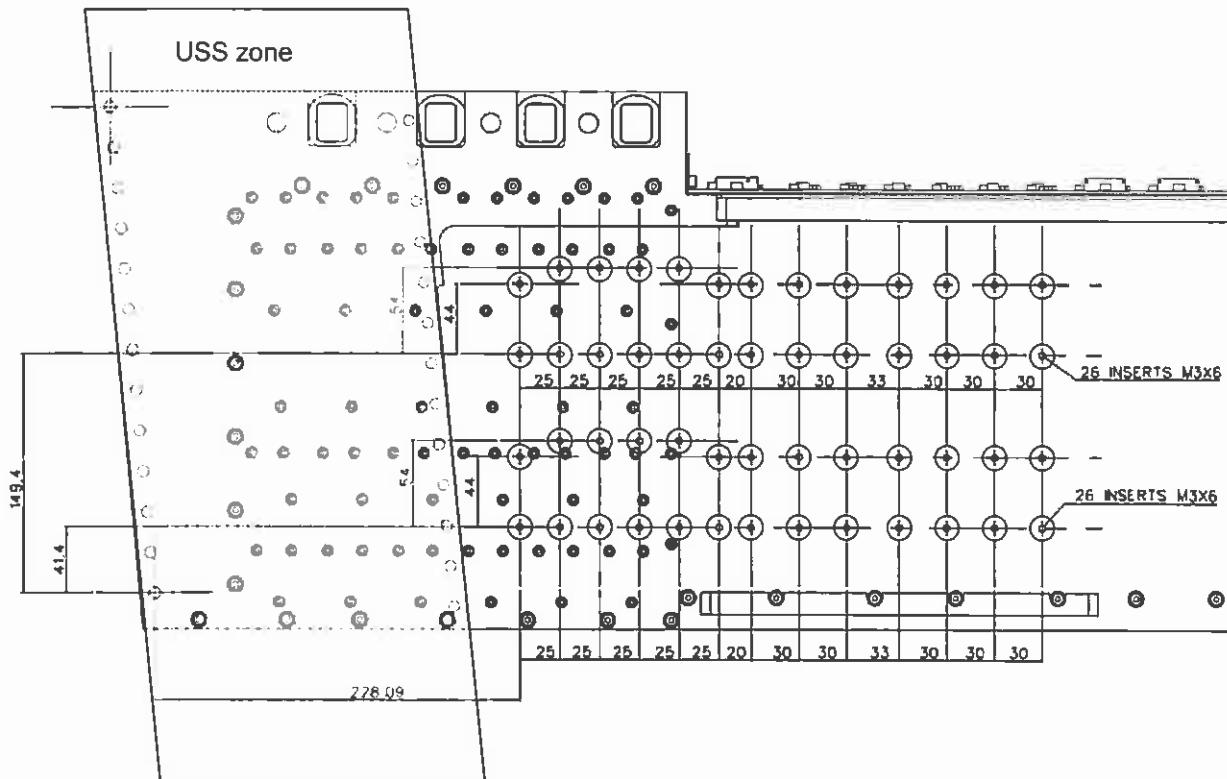


Fig. 6-10 CAB evaporator zone allowable area

It is necessary to find a correspondence of the mechanical interface with the thermal nodes.

The correspondence is given in the figure below: the node numbers are superimposed to the CAB wall view. Nodes are separated by light blue lines.



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SHT1 [DWG] WORK

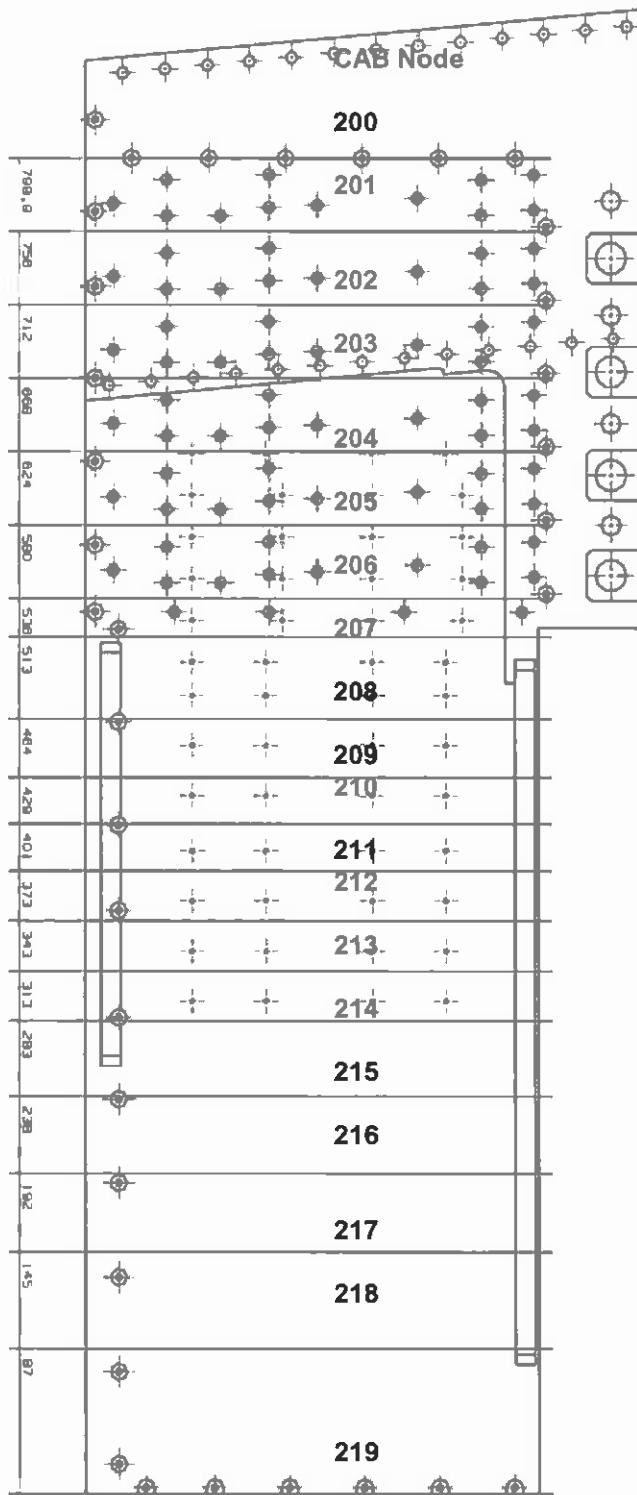


Fig. 6-11 CAB starboard side nodalization

The CAB side is divided into 20 slices, numbered from 200 to 219; the interface with evaporator starts from node 204, and potentially extends to node 214.



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In the figure, the exact quotes starting from the lower rim are displayed. This data is available in the following table:

Node:	Zmin (measured from lower edge)	to	Zmax (measured from lower edge)	Height [mm]
219	0.000	to	0.087	0.087
218	0.087	to	0.145	0.058
217	0.145	to	0.192	0.047
216	0.192	to	0.238	0.046
215	0.238	to	0.283	0.046
214	0.283	to	0.313	0.030
213	0.313	to	0.343	0.030
212	0.343	to	0.373	0.030
211	0.373	to	0.401	0.028
210	0.401	to	0.429	0.028
209	0.429	to	0.464	0.035
208	0.464	to	0.513	0.049
207	0.513	to	0.536	0.023
206	0.536	to	0.580	0.044
205	0.580	to	0.624	0.044
204	0.624	to	0.668	0.044
203	0.668	to	0.712	0.044
202	0.712	to	0.756	0.044
201	0.756	to	0.800	0.044
200	0.800	to upwards		N.A.

Tab. 6-5 CAB geometrical nodes layout: dimensions

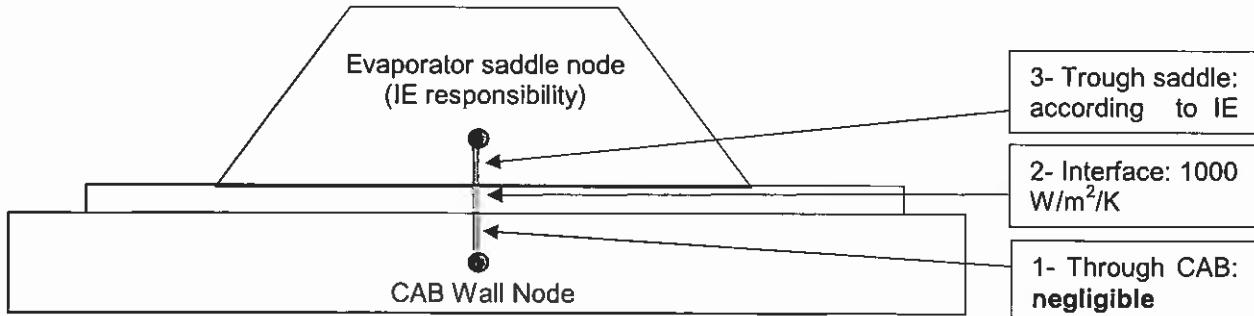
In order to reduce the number of diffusive nodes of the model and allow a proper management of the model with ECOSIMPRO software, the CAB nodes in the series x12 to x19 (where x=2,3,4,5 represent the series of each slice of the CAB nodalization) have been condensed in a unique node per series, with node number x12. Therefore, thermal capacitances have been properly summed, radiative couplings summed as well, sink temperatures have been averaged and environmental fluxes have been summed. The condensed nodes have been identified as the distant nodes from both the USS and the LHP interface, while the level of detail of the model has been kept high (as the original model) close to the main thermal interfaces.

Thermal links between CAB nodes and evaporators nodes shall therefore be in accordance to the correspondence above, and to the interface design by IE.

Regarding the conductance between CAB and Evaporator, the following interface conductance is to be considered: 1000 W/m<sup>2</sup>/K, being a thermal filler inserted at contact level..

Please consider the following scheme as a reference; in principle there are three contributions:

- 1) through the CAB skin, which is considered negligible
- 2) at the interface CAB evaporator interface (1000 W/m<sup>2</sup>/K)
- 3) from interface to saddle node, according to IE design and node location.



*Fig. 6-12 CAB Saddle thermal interface links components*

### 6.2.3.2 CONDENSER INTERFACE

The condenser interface is all along the radiator.

Preliminary routing has been provided in the specifications, but it shall be subjected to IE critical review.

The interface nodes for the LHP condenser are shown in the following scheme, where main dimensions of condenser are provided (for further details, see delivered CAD). The nodes location is represented by blue rectangles, with the associated node number. The preliminary condenser layout is shown in cyan, upper and lower lines are simply mirrored.

The radiator node number scheme is simple and can be used where the labels are not clear.

Radiator node number = 910XYY, where

- X represents the "row" of the radiator node and ranges from 1 to 7, and
- YY represents the "column" of the radiator node and ranges from 1 to 10.

According to the shape of the radiator, some columns may be missing.



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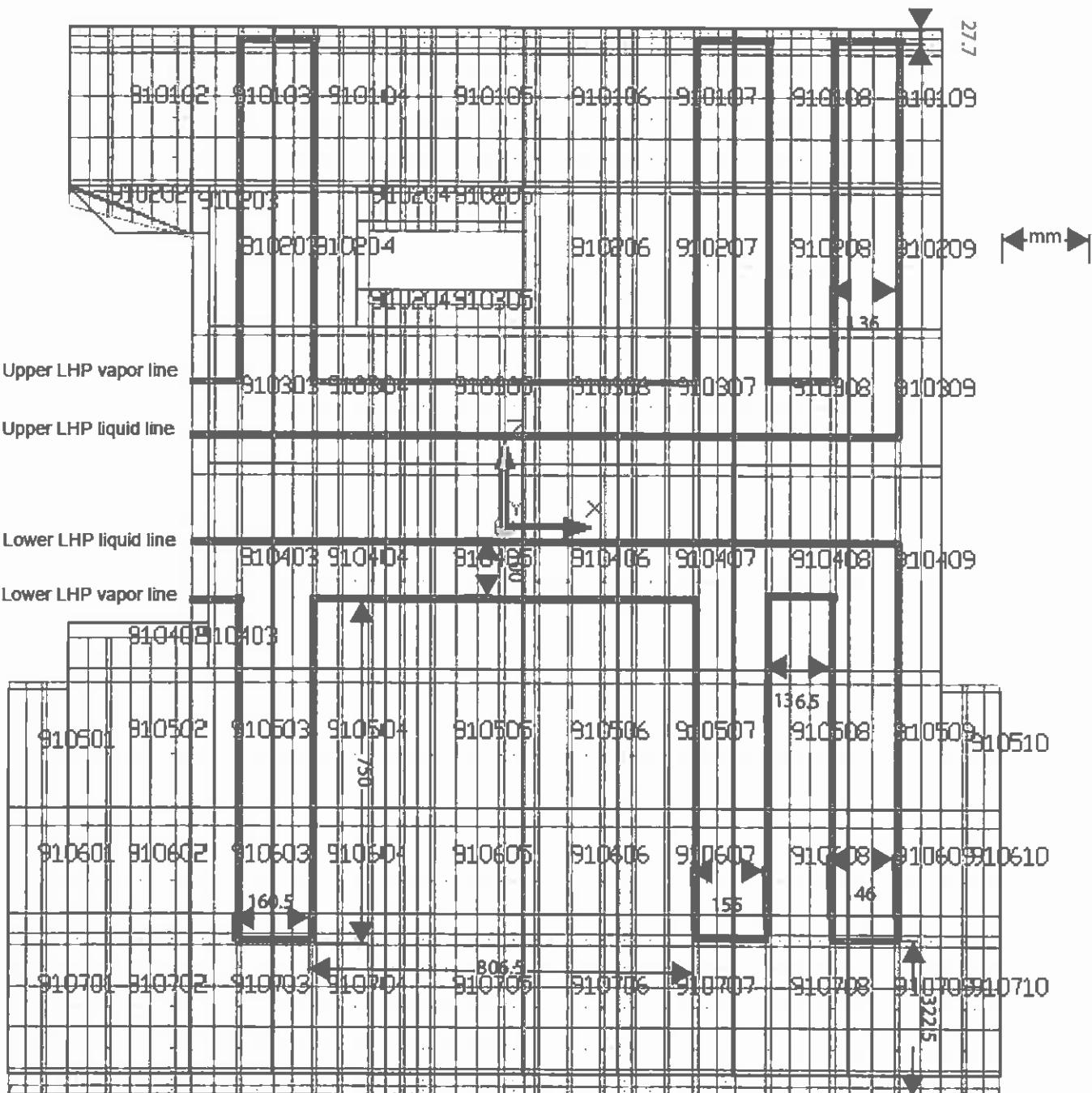
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Fig. 6-13 Wake radiator reduced model nodal layout

Regarding the interface conductance between radiator and condenser saddle, a similar approach to the previous one is used; the total heat path is composed by the series of three contributions

1. Conduction inside the saddle is a design parameter to be determined by IE
2. Interface conductance between saddle and radiator skin is evaluated as  $2000 \text{ W/m}^2/\text{K}$  in the model
3. conduction through the radiator skin from the condenser interface to the "average" surface, per unit length of condenser, is estimated to be  $3.1 \text{ W/m/K}$ .



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As an example, a condenser saddle 2 cm wide, which extends for 20cm on a radiator node, has a overall conductance to the radiator node equal to the series of:

- a) Interface contact conductance:  $2000 \text{ W/m}^2/\text{K} * 0.2 \text{ m} * 0.02 \text{ m} = 8.0 \text{ W/K}$
- b) radiator skin path:  $3.1 \text{ W/m/K} * 0.2 \text{ m} = 0.62 \text{ W/K}$

$$\text{Total} = 1/(1/8.0+1/0.62) = 0.58 \text{ W/K}$$

For calculating the length of condenser on the radiator nodes, the following dimensions are provided and considered enough accurate for modelling purposes:

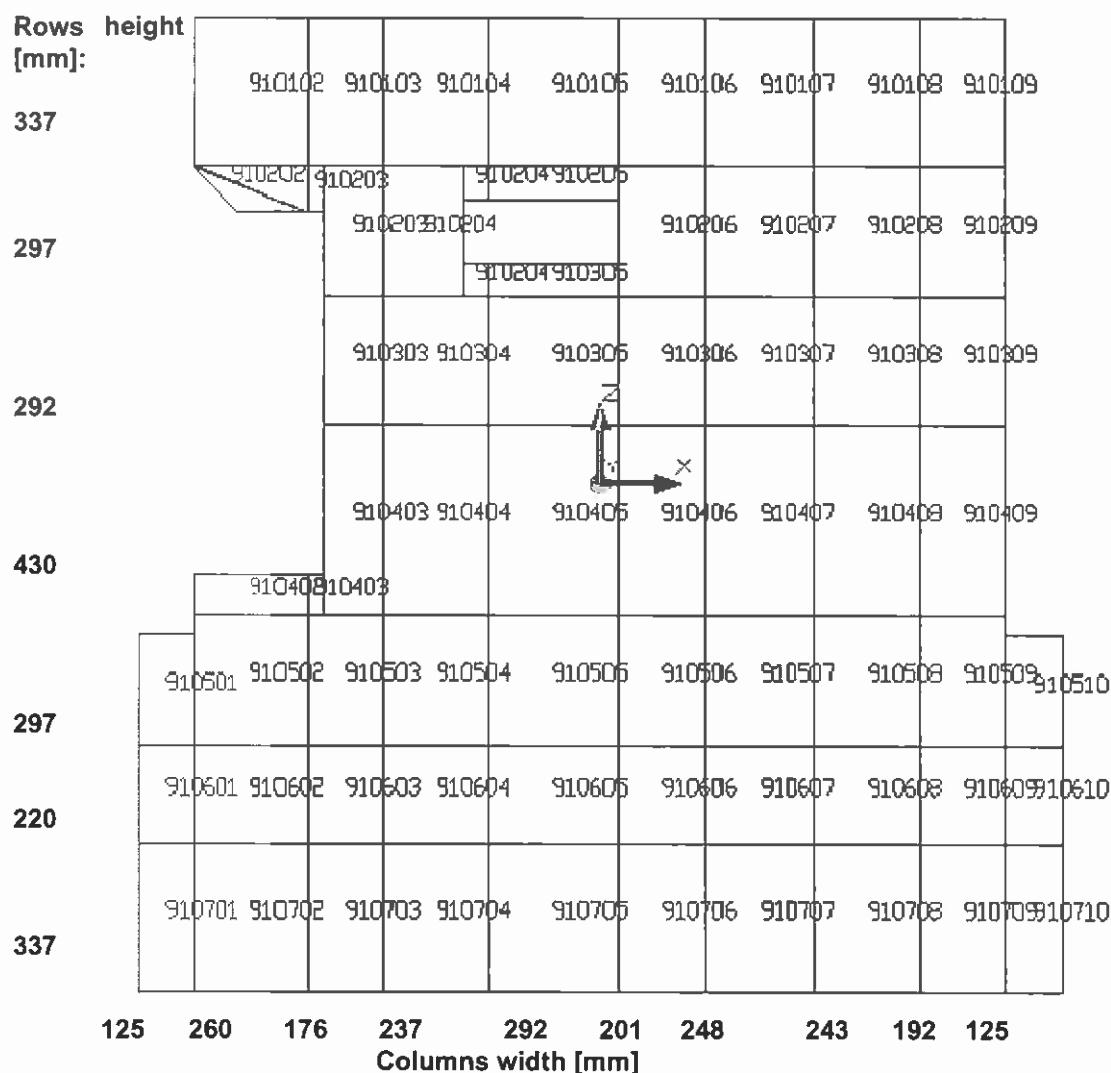


Fig. 6-14 radiator nodes dimensions



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dimension	value (mm)
height of row 1	337
height of row 2	297
height of row 3	292
height of row 4	430
height of row 5	297
height of row 6	220
height of row 7	337
width of column 1	125
width of column 2	260
width of column 3	176
width of column 4	237
width of column 5	292
width of column 6	201
width of column 7	248
width of column 8	243
width of column 9	192
width of column 10	125

Tab. 6-6 radiator nodes dimensions

### 6.2.4 FLUIDIC MODEL DESCRIPTION

The fluidic model is built in ECOSIMPRO, and incorporates the thermal network reported in section 6.2.2 (built according to CGS input). In addition, the LHP fluidic model has been implemented, according to the interfaces described in section 6.2.3.

The LHP modelling method and fluidic model description and parameters are provided in annex 1.



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## 7. ANALYSES RESULTS

The main analysis results are summarized in the following sections.

### 7.1 STEADY, WORST HOT CASE

The steady state power dissipation has been run with the system model, and the following environmental conditions:

Beta angle = -75°

Altitude: -15 +25 +15 (worst hot)

Environment: worst hot

System model: version 4.2

Other remarks: the system model had implemented the new debris shield.

The results are shown in the following figure:

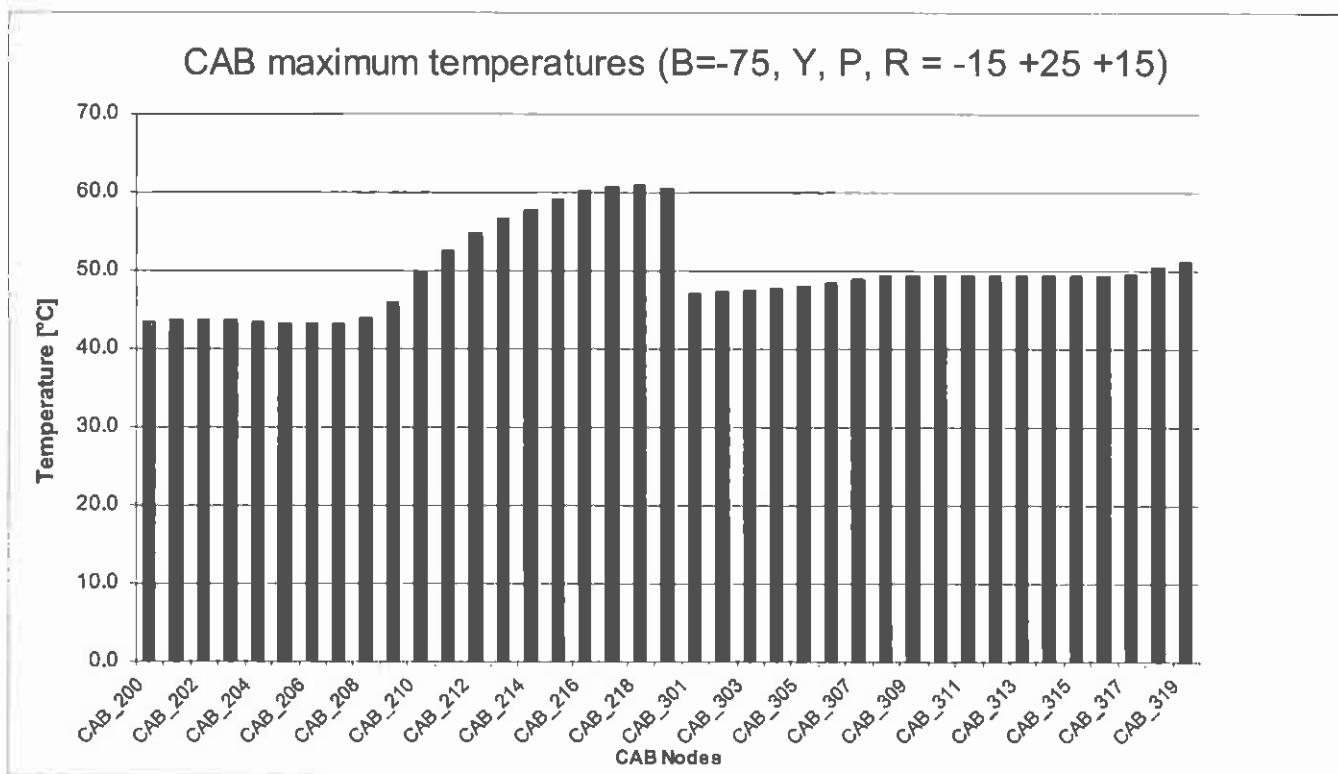


Fig. 7-1 CAB worst hot case, peak orbital temperature, along 2 CAB sides

The difference [Requirement – predicted temperature] is plotted in the next chart. Negative values represent violation of the requirements.



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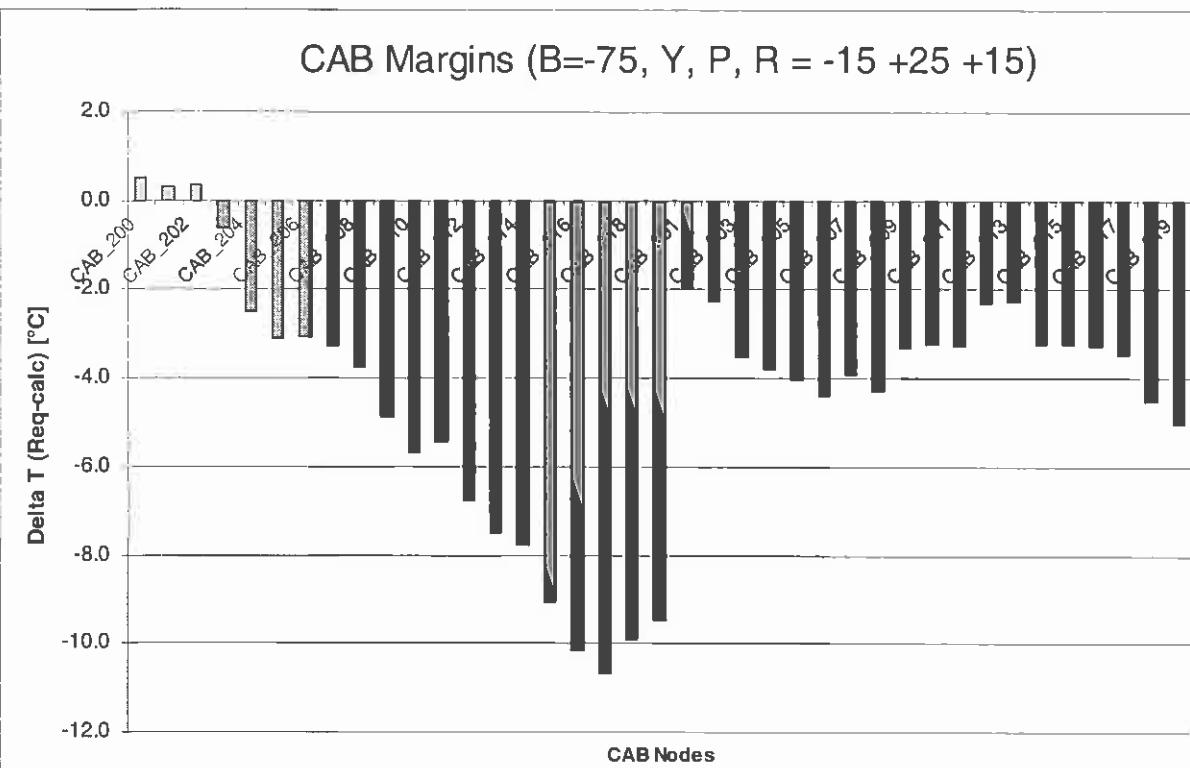


Fig. 7-2 CAB worst hot case, temperature margins along 2 CAB sides

As one can see, temperatures are mostly above the requirements (negative values in the plot above). The wake side (node series 3xx, at the right of the plot) is in average 3°C above the requirements. The starboard side (series 2xx, at the left of the plot) presents larger violations, which reach the peaks of -10°C on the lower part of the CAB (nodes 212 to 219).

Considering that

1. the attitude  $-15^\circ +25^\circ +15^\circ$  is unlikely, and that the CAB is properly working under the same beta angle range, but in the most likely attitudes (0,0,0, which is similar to MPA and TEA attitudes from the thermal point of view – see the next section),
2. the extreme beta angles at which the worst cases occur are a small percentage of the total mission time, it is unlikely that CAB would require operational limitations.

Corrective actions in case of superposition of extreme hot beta angle and extreme hot attitude shall be agreed with the unit supplier, requiring either

- a power reduction, OR
- an operational limitation, OR
- a temporary acceptance of electrical components de-rated temperature limit violation.

## 7.2 STEADY, TYPICAL HOT CASE

The steady dissipation of the CAB has been applied also to a less demanding orbit, with similar hot environment but a typical attitude of the ISS (Yaw, pitch and roll set to 0). This orbital parameters are also representative of the MPA and TEA attitudes. The simulation parameters are:

Beta angle =  $-75^\circ$

Attitude: 0,0,0 (typical)

Environment: worst hot

System model: version 4.2

Other remarks: the system model had implemented the new debris shield.

The results are shown in the following figure:



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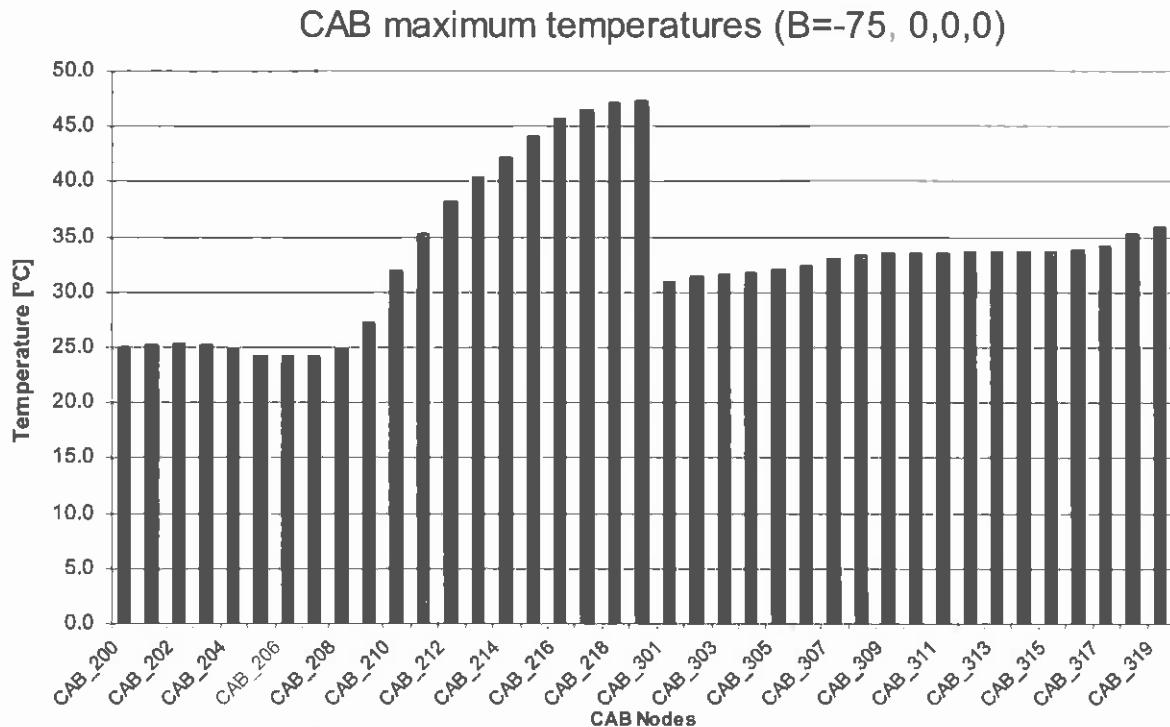
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Fig. 7-3 CAB typical hot case, peak orbital temperature, along 2 CAB sides

The difference [Requirement – predicted temperature] is plotted in the next chart. Positive values represent requirements fulfillment.

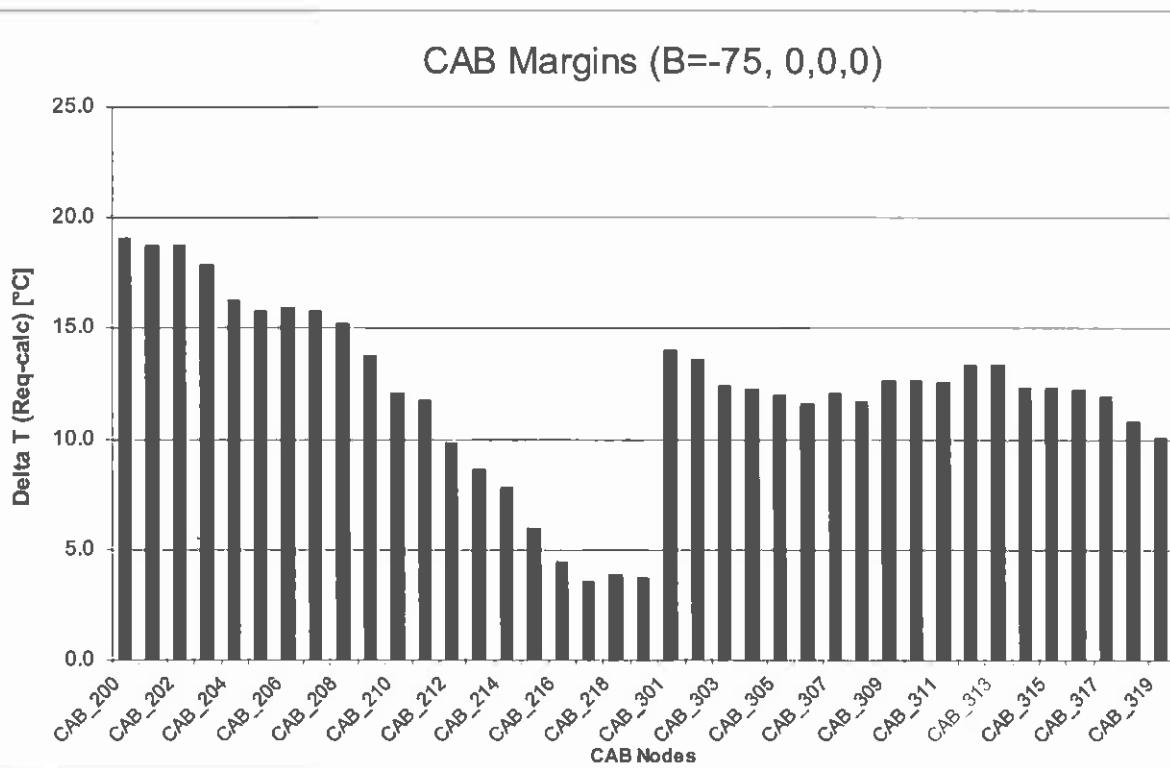


Fig. 7-4 CAB typical hot case, temperature margins along 2 CAB sides



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All locations give positive temperature margins, ranging from 4°C (in the hottest CAB locations, on the starboard face in the lower part) up to 18°C margin on the USS-02 connected nodes.

### 7.3 RAMP IN HOT CASE

The ramp up case has been run with the 2-phase model, and the following environmental conditions:

Beta angle = -50°

Altitude: 0°, 0°, 0°

Environment: worst hot

System model used to generate interface data to 2-phase model: version 4.2

Other remarks: 1. The system model had not yet the debris shield. The 2-phase model accounted for this fact by suppressing heat loads and radiative couplings on the CAB side (starboard) which is facing the debris shield, considering hence this face adiabatic.

2. The LHP was considered not working until the CAB power ramp (time = 57000 seconds), since the radiator temperature is comparable to the CAB ones in the steady part of the simulation. LHP is ON only since the CAB power ramp-up, when large amount of power is applied. This is a conservative assumption.

The results are shown in the following figure:

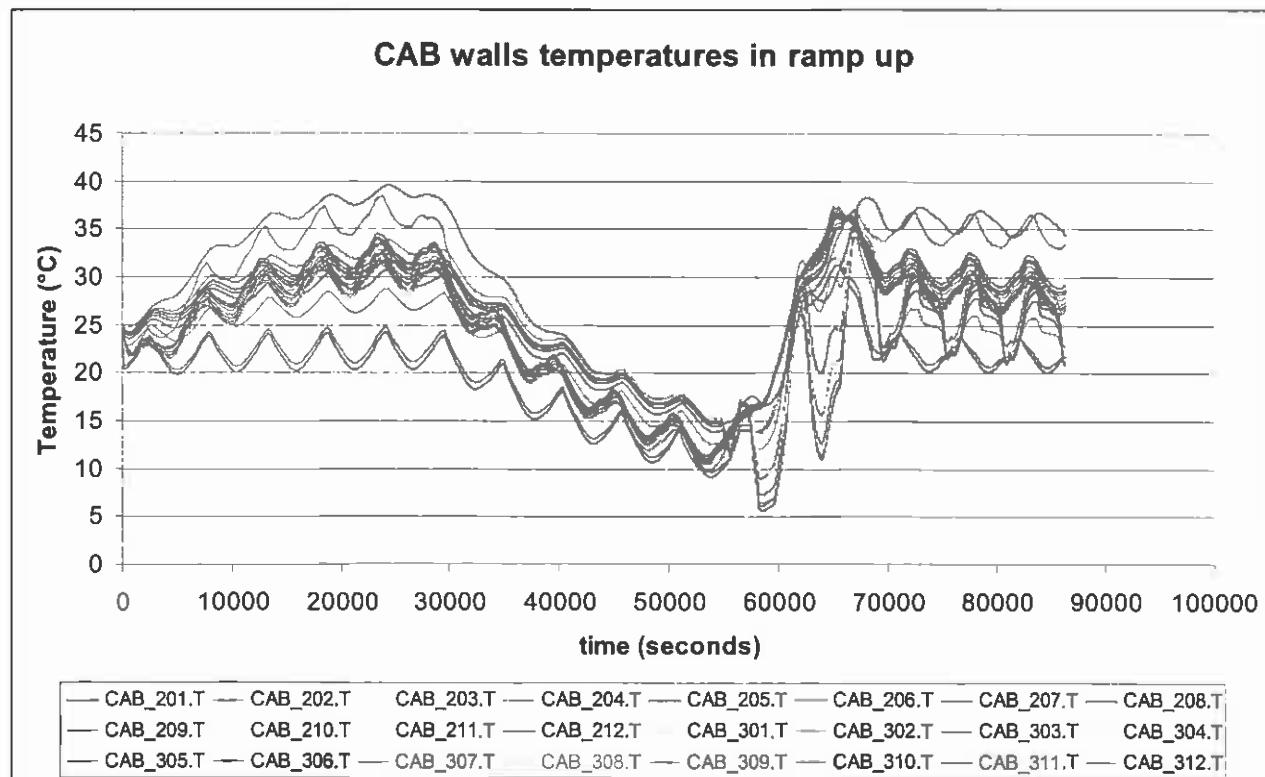


Fig. 7-5 Ramp up CAB temperature profiles

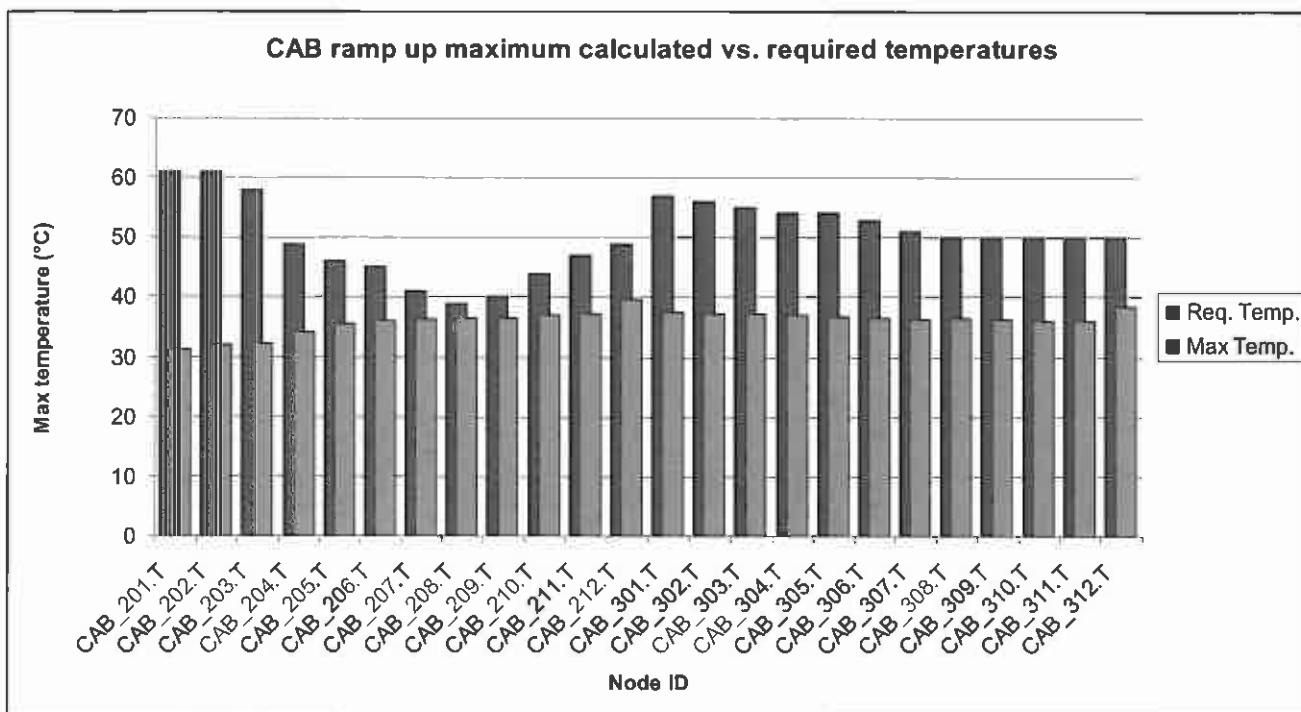


Fig. 7-6 Ramp up CAB maximum temperatures versus requirements

All margins are positive, the calculated temperature is always below the maximum required temperature.

As a reference, the heat flux on towards the various CAB boundary elements are provided in the following figure. As explained, there are no flux through the LHP until the start of the ramp-up.

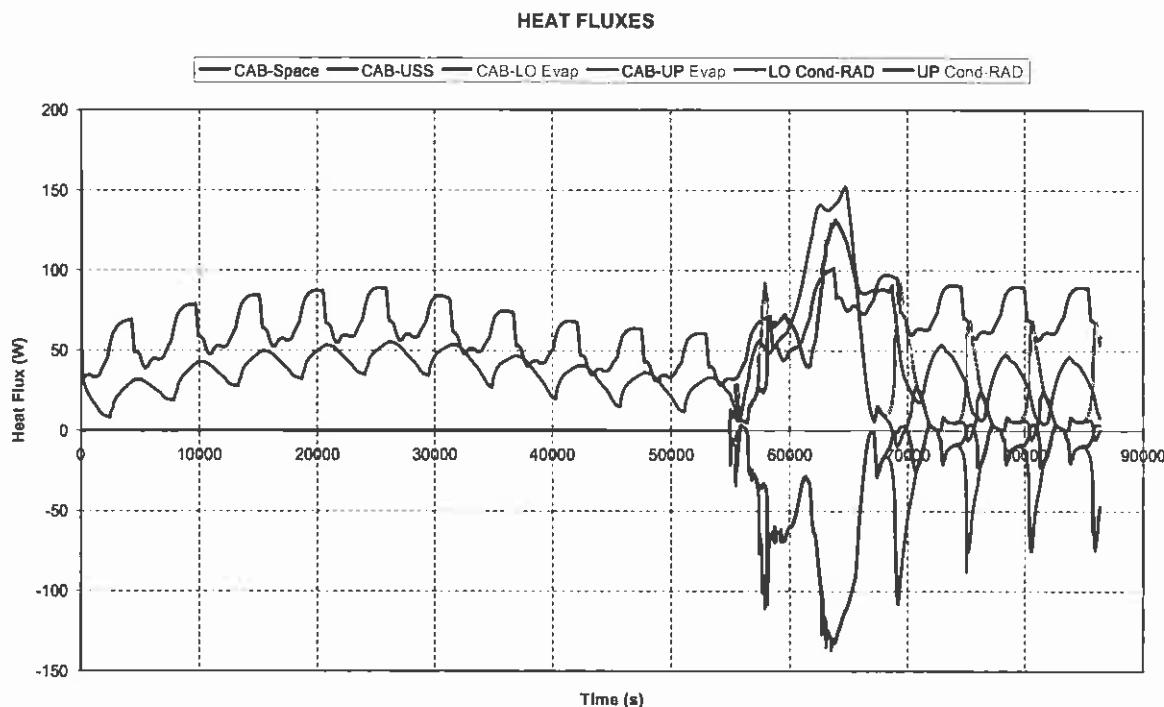


Fig. 7-7 Ramp up CAB maximum temperatures versus requirements



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## 7.4 SWITCH ON

The heaters set (2 patches) has been powered at 100W (50+50W) in order to verify the ability of the power to bring the CAB above its switch on temperature (-25°C) in the worst cold environment of the coldest orbital configuration (beta +75°, attitude -15;-20;+15 Yaw,Pitch,Roll).

In the simulation, the system level model has been used, in the following configuration:

- Heaters are always ON (no thermostat regulation effect); the goal is just to verify the ability of the heaters to bring the CAB above the switch ON temperature
- AMS model in OFF mode (no power dissipation of other electronics crates and detectors)
- LHP Bypass valve in off (bypass) mode.
- Minimum power (100W, at 113VDC)

The temperature plots along one orbit are the following:

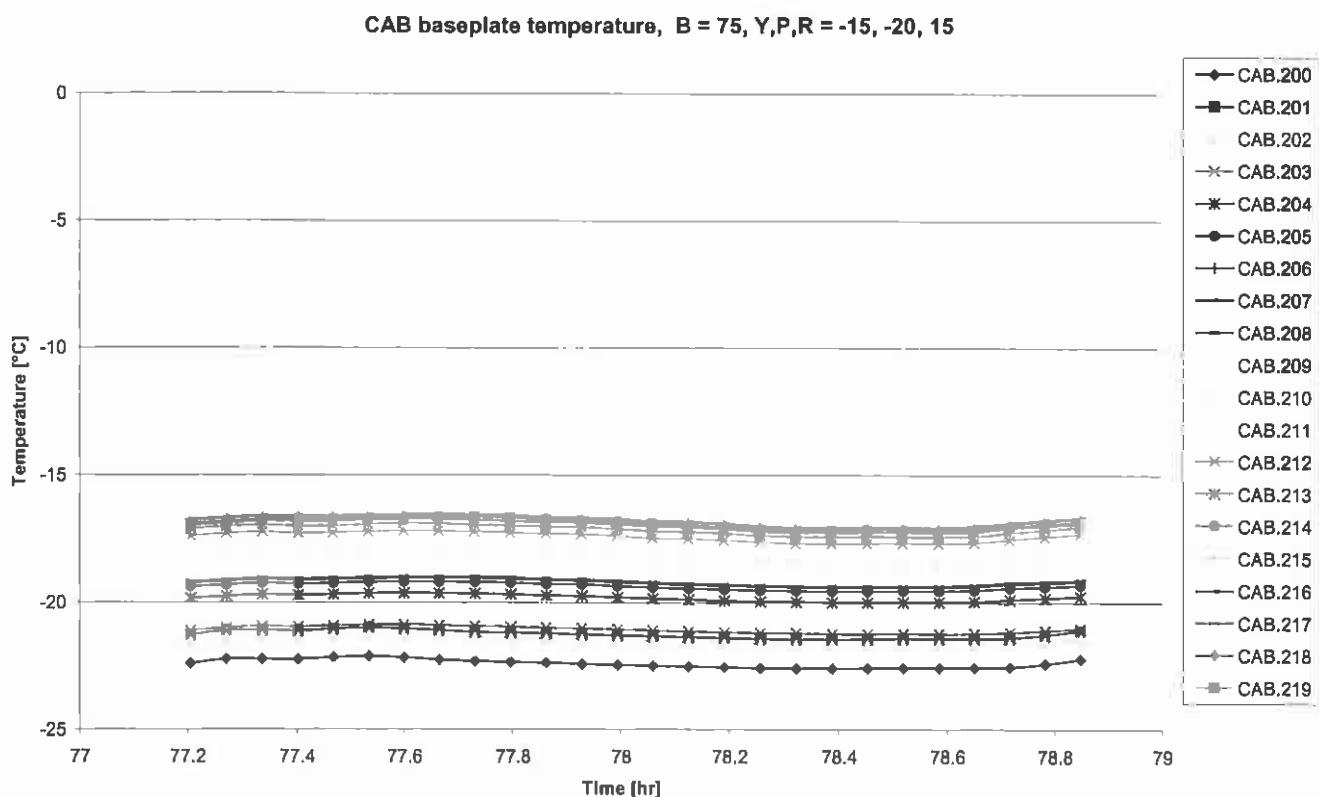


Fig. 7-8 Heaters for CAB switch On: baseplate side



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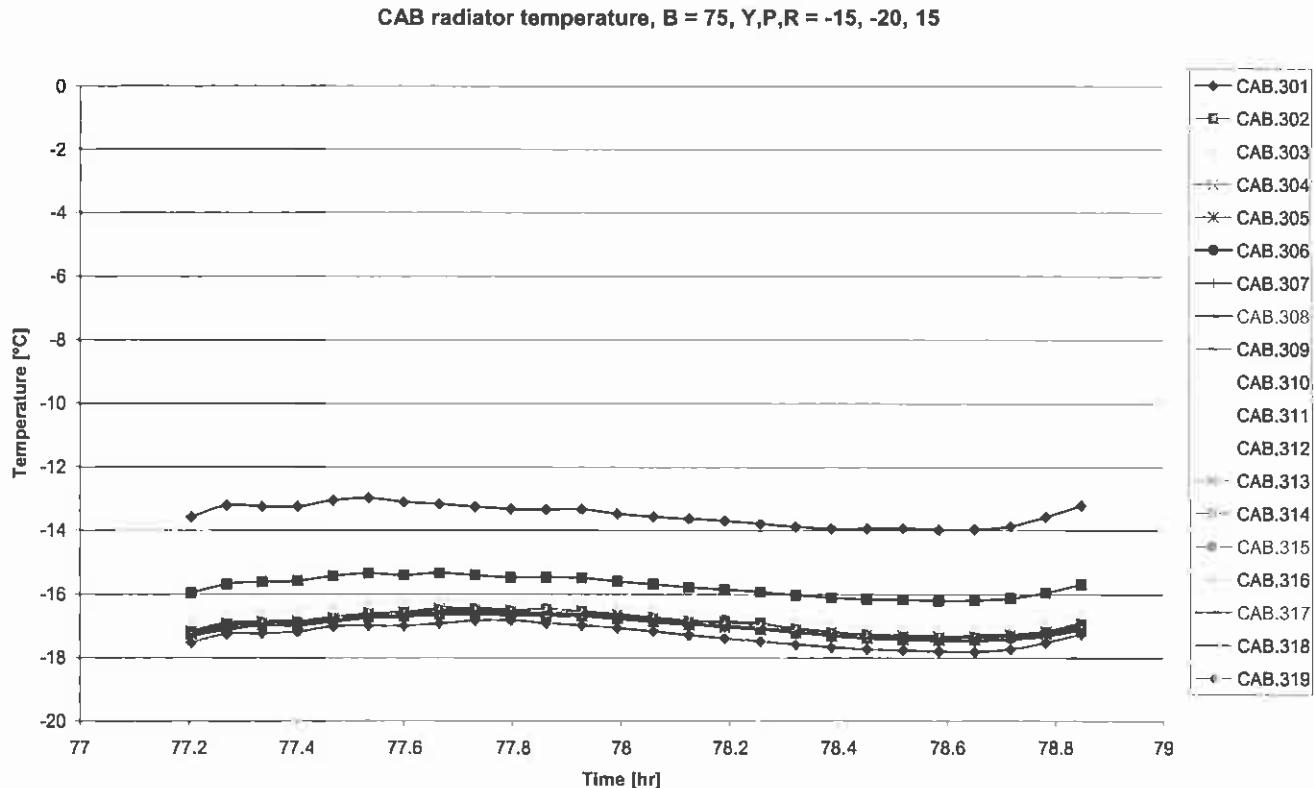


Fig. 7-9 Heaters for CAB switch On: radiator side

All temperatures are above the minimum switch on level in the worst orbital case.  
The heaters are properly sized to allow CAB switch on.

## 7.5 COOLING DOWN

The cooling down scenario represents an off-nominal case where AMS is left unpowered for 8 hours. No power dissipation takes place on the system during this time.

During these period CAB is able to survive above its minimum non operative temperature (-40°C ).  
The minimum temperature experienced by the CAB wake and starboard walls is -36.7°C.

The initial temperatures of the CAB are derived in the worst cold case, with the minimum power dissipation set to 35W.

The environmental temperatures are proper of the cold cases: worst cold environment and coldest orbital configuration (beta +75°, attitude -15°;-20°;+15° Yaw,Pitch,Roll).



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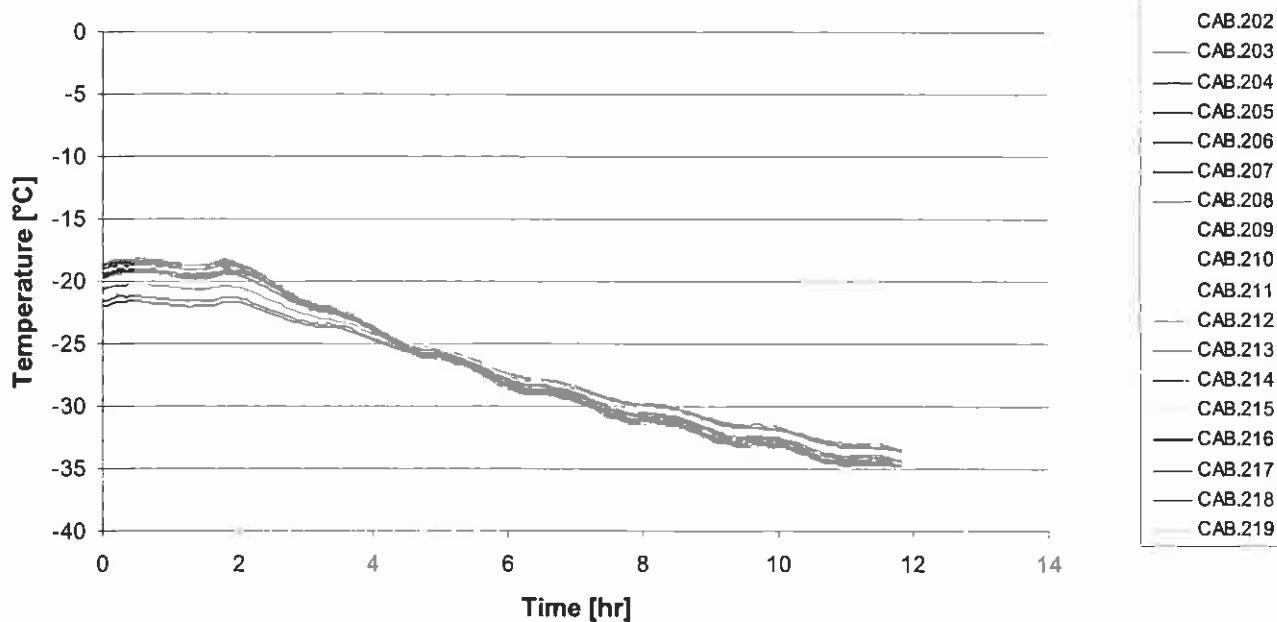
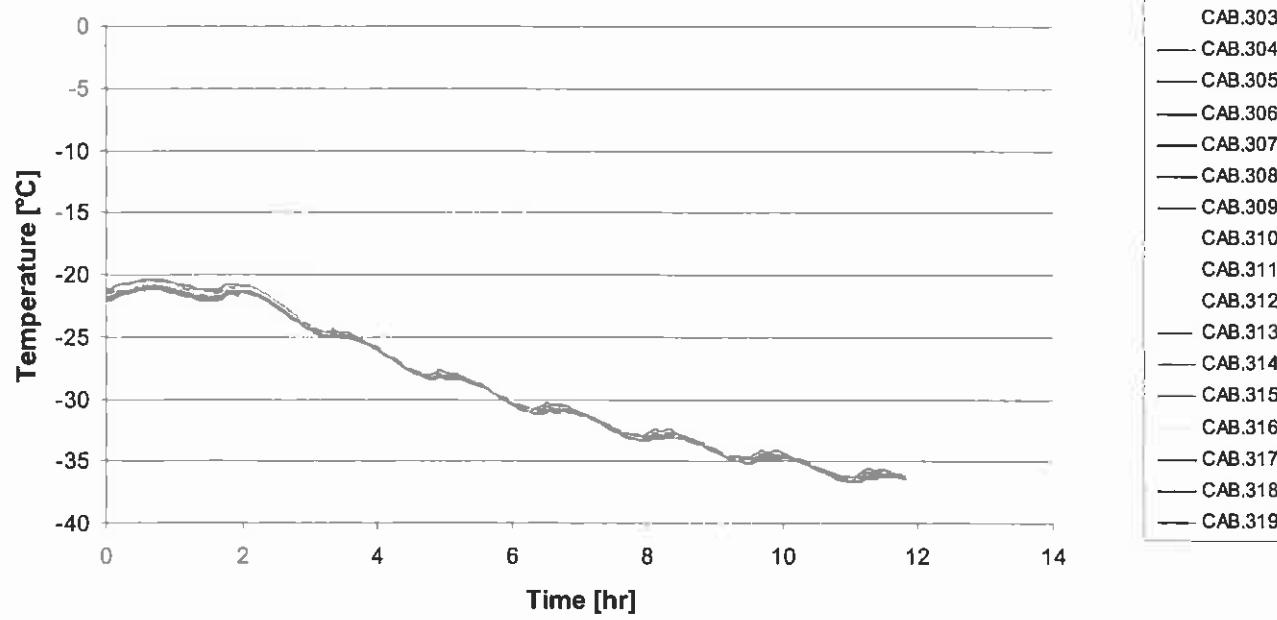
**CAB baseplate B= 75 Y,P,R=-15,-20,15  
CAB steady @ 35W****CAB radiator B= 75 Y,P,R=-15,-20,15  
CAB steady @ 35W**

Fig. 7-10 Cooling down CAB temperatures



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## 8. CONCLUSIONS

The CAB shows positive margins in the relevant Hot cases (ramp-up and typical hot case). The CAB heaters are sufficient to bring the temperature above the switch on temperature.

The only requirements violation is found in the extreme beta angle range, when combined with the worst attitude. Considering that

1. the attitude  $-15^\circ +25^\circ +15^\circ$  is unlikely, and that the CAB is properly working under the same beta angle range, but in the most likely attitudes (0,0,0, which is similar to MPA and TEA attitudes from the thermal point of view),
2. the extreme beta angles at which the worst cases occur are a small percentage of the total mission time, it is unlikely that CAB would require operational limitations.

Corrective actions in case of superposition of extreme hot beta angle and extreme hot attitude shall be agreed with the unit supplier, requiring either

- a power reduction, OR
- an operational limitation, OR
- a temporary acceptance of electrical components de-rated temperature limit violation.



CARLO GAVAZZI SPACE SpA

# AMS02 - TCS

CAB TCS THERMAL ANALYSIS REPORT

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## ANNEX 1. CAB LHPS – 2 PHASE MODEL DESCIRPTION

## 5. CAB LHP'S MODELLING

### 5.1 ECOSIMPRO LIBRARY GENERALITIES

To design the LHPs and to verify its performances, a thermal model, including the thermal interface model provided by CGS, has been developed using the mathematical tool EcosimPro [RD1]. To fully understand the model, an overview of the mathematical formulation used in general for the modelling is given hereafter.

#### 5.1.1 Mathematical formulation

The mathematical model has been built modularly. This means that each complete LHP model has been created connecting the typical LHP components: evaporator, compensation chamber, transport lines, condenser and pressure regulator valve. The main assumptions made in all the components are as follows:

- The 1D fluid flow model is a homogeneous equilibrium model (HEM). That is, the one-dimensional conservation equations are established for the two-phase mixture and the amount of vapour and liquid is taken into account in terms of quality. It is considered that the two phases are in equilibrium assuming equal phase velocities, temperatures and pressures.
- The calculated thermodynamic properties correspond to the two-phase mixture. However, in saturation conditions the thermodynamic properties are calculated separately for vapour and liquid phases. The thermodynamic properties are obtained by interpolation using the tables built from NIST [RD2] routines.
- The LHP components can exchange heat with the environment by convection and radiation, and they can exchange heat with other external components (such as saddles) by conduction.
- The fluid model is based on the one dimensional fundamental conservation equations (mass, momentum and energy) applied to control volumes. The fluid part of each LHP component is sub-divided into individual control volumes.
- The compressibility and transient effects are also taken into account. The viscous effects are taken into account through the pressure drop calculations. The pressure drop calculations use the built-in EcosimPro functions for different elements. These include empirical correlations for the pressure drop in a porous media.
- The gravity effects due to the different orientations of the LHP have been taken into account in the formulation.

#### PRESSURE REGULATOR VALVE

The mass and energy conservation equations are applied for the fluid contained in the valve in order to obtain the density and the internal energy at any time. To fix the valve set point, the model requires an input temperature value ( $T_{open}$ ). The saturation pressure corresponding to this tem-

perature ( $P_{open}$ ) is obtained by interpolation using the tables from NIST and represents the point where the valve opens completely the bypass path and, consequently, the radiator branch is completely closed. Taking into account the properties of the valve bellows, a new pressure ( $P_{close}$ ) is calculated to define the point where the valve starts to open the bypass path and part of the mass flow goes through the radiator and part of the mass flows through the bypass line to the compensation chamber.

The valve position is calculated depending on the relation between the fluid pressure and these values of  $P_{open}$  and  $P_{close}$  as follows:

$$\begin{aligned} pos = 0 & \quad P_{fluid} \geq P_{close} \\ 0 < pos < 1 & \quad P_{close} > P_{fluid} > P_{open} \\ pos = 1 & \quad P_{fluid} \leq P_{open} \end{aligned}$$

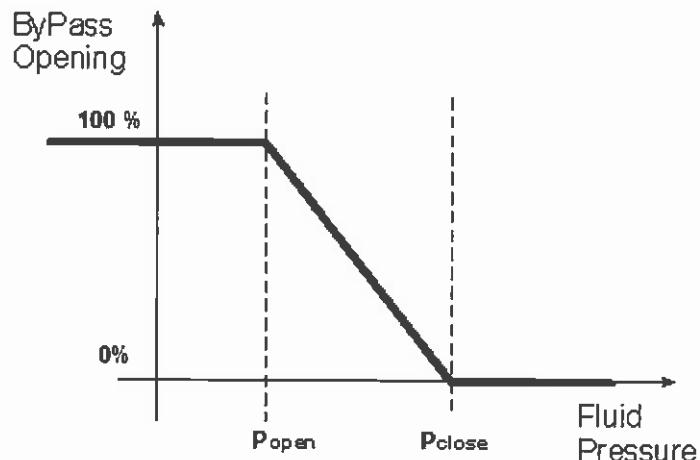


Figure 5-1 : Valve position

Therefore, in regulation conditions, it is assumed that the valve reaches a steady state in an intermediate position between 0 and 1.

Finally, the momentum equation is solved for each of the branches (direct and bypass) taking into account the value of the valve position.

## 5.2 MODEL FOR THE LHP'S DESIGN

### 5.2.1 Sizing of the compensation chamber and fluid inventory calculation

The compensation chamber size and the fluid inventory are determined to fulfil the following conditions:



- Under the cold case some liquid is left in the compensation chamber when the rest of the loop is flooded.
- Under the hot case some vapour space is available in the compensation chamber.

Taking into account these conditions, a function has been developed using EcosimPro to calculate the exact values of the compensation chamber volume and the fluid inventory.

To determine these parameters, a separated model has been created for each CAB LHP considering only its geometrical characteristics. These models require operating temperature range input data. These temperature ranges, according to the specifications [AD2], are the following:

- Maximum Operating Temperature = 55.5 °C.
- Minimum Operating Temperature for the Capillary Pump = -40 °C.
- Minimum Operating Temperature for the Vapour Line = -55 °C.
- Minimum Operating Temperature for the Liquid Line = -55 °C.
- Minimum Operating Temperature for the Condenser = -70 °C.

Finally, the results provided by this function are presented in the following figures:

## FLUID INVENTORY

	MASS (g)	VOLUME (cc)	
Evaporator	45.64	Compensation Chamber	94.48
Vapour Line	53.66	LHP	177.19
Condenser	330.99	Vapour Line	8.60
Liquid Line	29.08	Wick (without hole)	15.88
CompChamber	84.58	Hole	4.69
Wick	100.94	Condenser	53.01
Fluid inventory	59.18	Axial Grooves	1.94
Total	702.97	Liquid Line	2.60
		Circumferential Grooves	0.49

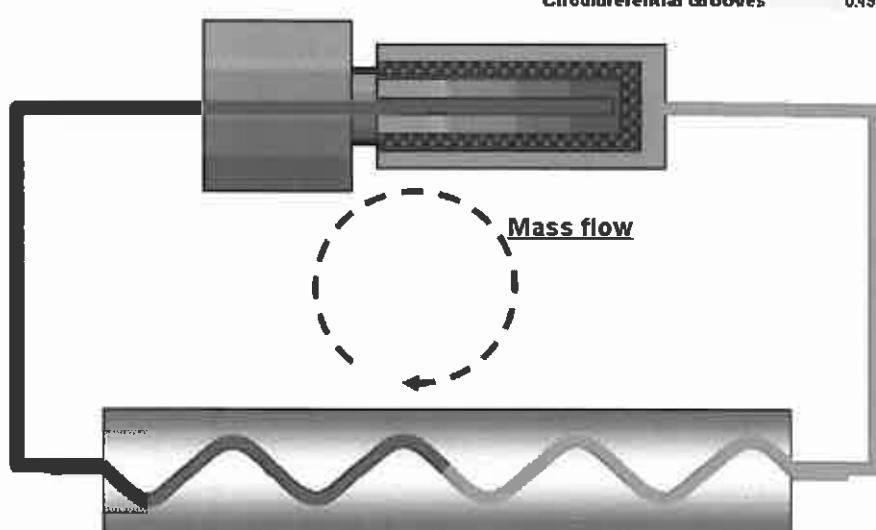


Figure 5-2 : Upper LHP fluid inventory

## FLUID INVENTORY

	MASS (g)	VOLUME (cc)	
Evaporator	45.54	Compensation Chamber	94.79
Vapour Line	55.60	LHP	177.45
Condenser	330.98	Vapour Line	8.90
Liquid Line	24.40	Vick (without hole)	15.88
CompChamber	84.59	Hole	4.69
Vick	100.94	Condenser	53.01
Fluid inventorg	59.14	Axial Grooves	1.93
Total	701.10	Liquid Line	2.43
		Circumferential Grooves	0.49

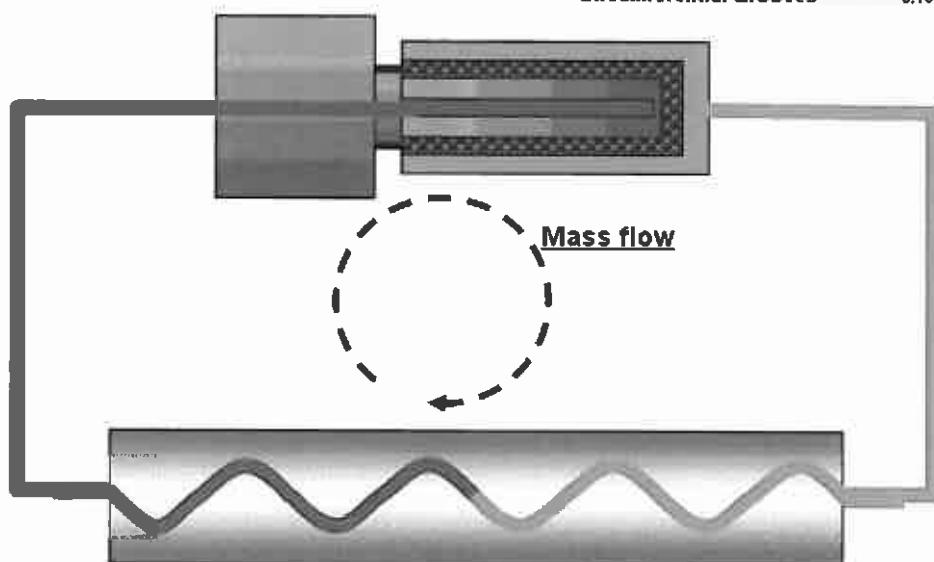


Figure 5-3 : Lower LHP fluid inventory

### 5.3 MODEL FOR THE LHP'S PERFORMANCES VERIFICATION

#### 5.3.1 Model Description

##### 5.3.1.1 *Main assumptions*

The main general assumptions made in this particular model are:

- The LHP components do no exchange heat with the ambient.
- The thermal coupling between the evaporator and the compensation chamber is set to 0.1 W/K.
- All the test correction factors have been set to 1.

##### 5.3.1.2 *Thermal Interface Model*

According to the references AD3-AD6, a thermal interface model has been created in EcosimPro including the following components:

- **CAB Thermal Network:** It is represented by 91 diffusive nodes interconnected by 221 thermal couplings. Most of these couplings (209) are linear and the others (12) are radiative.
- **CAB Environment:** It is modelled by 40 boundary nodes (39 nodes represent the sink and 1 represents the USS). The CAB nodes are connected with their corresponding sink nodes via GR components (63 radiative couplings) and 4 CAB nodes are connected to the USS node by GL components (4 linear couplings).
- **RAD Thermal Network:** It is represented by 149 diffusive nodes interconnected by 467 linear couplings.
- **RAD Environment:** It is modelled by 93 boundary nodes which represent the sink. The RAD nodes are connected to these sink nodes via GR components (122 radiative couplings).

##### 5.3.1.3 *Complete Thermal Model*

The previous interface model is connected to the two CAB LHPs via GL components. The values of the evaporator couplings are calculated as follows:

$$GL = A_{cont} \cdot k_{cont}$$

Considering the given value of  $k_{cont} = 1000 \text{ W/m}^2/\text{K}$ , the calculated values are listed in the following table:

CAB Node	GLs with Evaporator Saddle (per LHP)(W/K)
204	0.726
205	2.904
206	2.904



CAB Node	GLs with Evaporator Saddle (per LHP)(W/K)
207	1.518
208	2.744
209	1.624

Table 5-1 : CAB – Evaporator thermal couplings

The values of the condenser couplings per length are calculated as follows:

$$\frac{GL_{tot}}{m} = \left( \frac{1}{GL_1} + \frac{1}{GL_2} + \frac{1}{GL_3} \right)^{-1} W/m/K$$

The previous GLs are described and calculated here below:

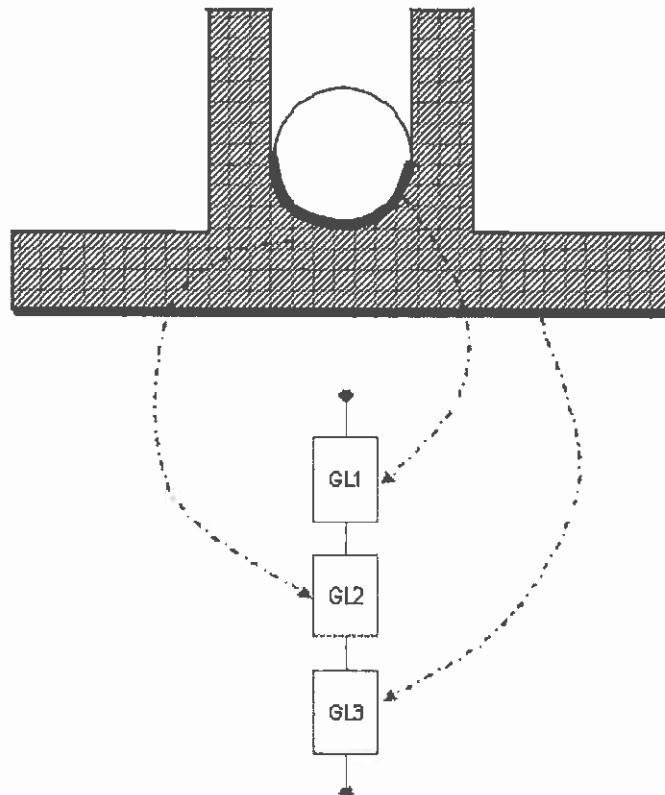


Figure 5-4 : Condenser thermal couplings

$GL_1 = 770 \text{ W/m/K}$  – Thermal coupling because of the soldering.

$GL_2 = 684 \text{ W/m/K}$  – Thermal conduction through the saddle.

$$GL_3 = \left( \frac{1}{W_{cont} \cdot k_{cont}} + \frac{1}{k_{cond}} \right) \text{ W/m/K}$$

To facilitate the calculations, the total length of each condenser is divided into 25 nodes as it is shown in the next picture:

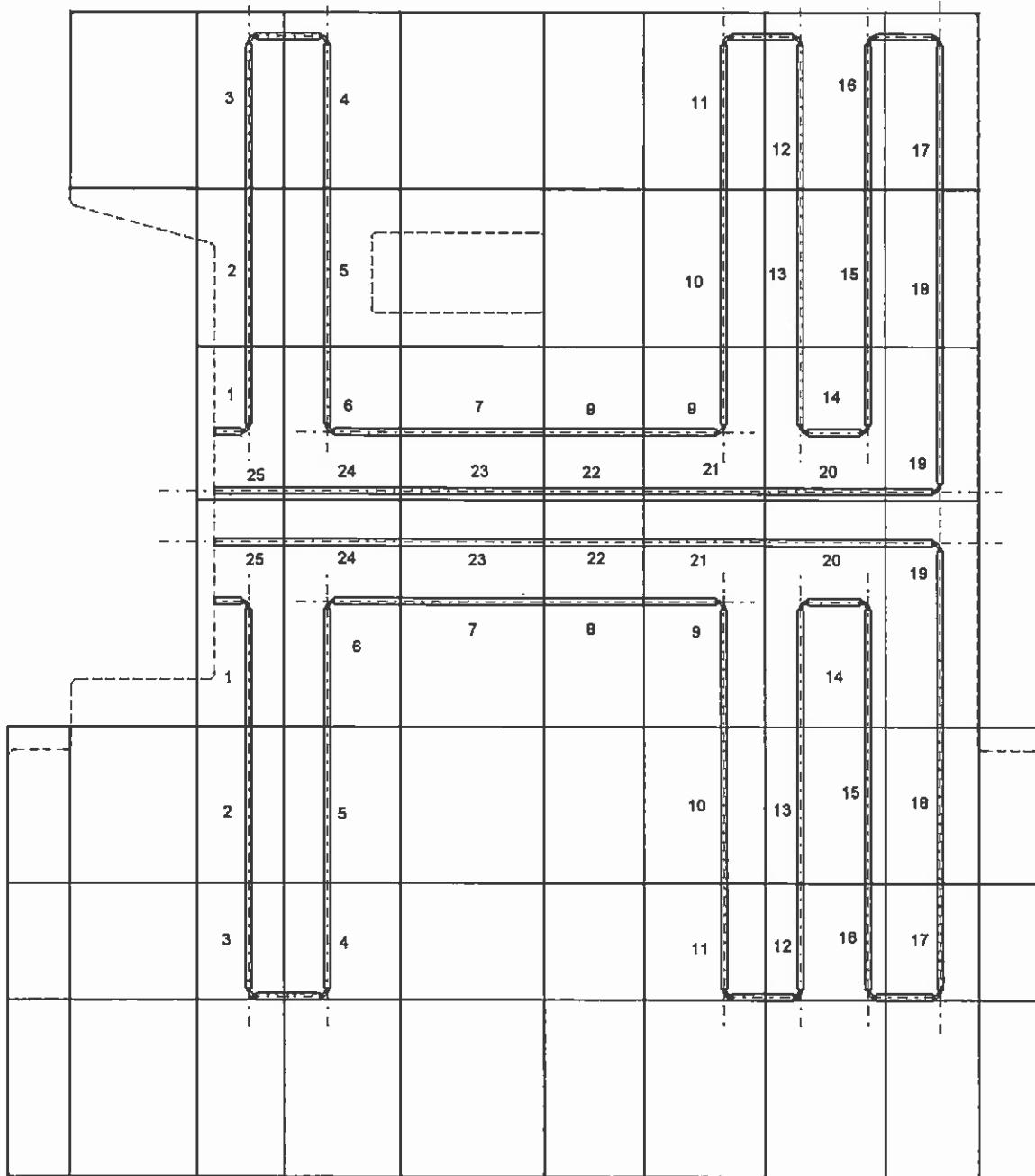


Figure 5-5 : Condenser length discretization

Therefore, considering the given values of  $k_{cont} = 2000 \text{ W/m}^2/\text{K}$  and  $k_{cond} = 3.1 \text{ W/m/K}$ , the calculated values of the total GLs are listed in the following table:

UPPER LHP			LOWER LHP		
COND Node	RAD Node	GL <sub>tot</sub> (W/K)	COND Node	RAD Node	GL <sub>tot</sub> (W/K)
1	910303	0.512	1	910403	0.703
2	910203	0.756	2	910503	0.756
3	910103	0.847	3	910603	0.656
4	910104	0.886	4	910604	0.695
5	910204	0.756	5	910504	0.756
6	910304	0.717	6	910404	0.908
7	910305	0.743	7	910405	0.743
8	910306	0.512	8	910406	0.512
9	910307	0.757	9	910407	0.947
10	910207	0.756	10	910507	0.756
11	910107	0.875	11	910607	0.684
12	910108	0.844	12	910608	0.653
13	910208	0.756	13	910508	0.756
14	910308	1.023	14	910408	1.405
15	910208	0.756	15	910508	0.756
16	910108	0.751	16	910608	0.561
17	910109	0.945	17	910609	0.754
18	910209	0.756	18	910509	0.756
19	910309	0.905	19	910409	1.096
20	910308	0.618	20	910408	0.618
21	910307	0.631	21	910407	0.631
22	910306	0.512	22	910406	0.512
23	910305	0.743	23	910405	0.743
24	910304	0.603	24	910404	0.603
25	910303	0.359	25	910403	0.359

Table 5-2 : RAD – Condenser thermal couplings

Finally, the main input data introduced in the LHP components are summarized in the next tables:

- DATA:

DESCRIPTION	VALUE	UNITS
LHP Working fluid	Ammonia	-

- COMPONENT –CAPILLARY PUMP for both LHPs

DESCRIPTION	VALUE	UNITS
Heat capacity of the compensation chamber case (Cp*m)	35	J/K
Elevation of the compensation chamber	0	m
Thermal coupling between the evaporator and the compensation chamber	0.1	W/K
Superheating required for evaporation start-up	0.1	K



DESCRIPTION	VALUE	UNITS
Number of axial grooves	4	-
Heat capacity of evaporator case	24	J/K
Material of the evaporator case	Stainless Steel	-
Vertical coordinate of evaporator center	0	m
Shape of the axial grooves	Rectangular	-
Wick external diameter	0.014	m
Primary wick material	Nickel	-
Heat capacity of the saddle	318	J/K
Thermal conductance between the saddle and the evaporator case	66.5	W/K

- COMPONENT – BYPASS VALVE for both LHPs

DESCRIPTION	VALUE	UNITS
Temperature to open completely the bypass branch	263.15	K
Bottom elevation relative to a z fixed axis	0	m

- COMPONENT – UPPER VAPOUR LINE

DESCRIPTION	VALUE	UNITS
Inner diameter of the pipe	0.003	m
External diameter of the pipe	0.004	
Total pipe length	1.216	m
Nodes of the pipe	2	-
Wall material	Stainless Steel	-

- COMPONENT – UPPER LIQUID LINE

DESCRIPTION	VALUE	UNITS
Inner diameter of the pipe	0.002	m
External diameter of the pipe	0.003	
Total pipe length	0.891	m
Nodes of the pipe	2	-
Wall material	Stainless Steel	-



- COMPONENT – LOWER VAPOUR LINE

DESCRIPTION	VALUE	UNITS
Inner diameter of the pipe	0.003	m
External diameter of the pipe	0.004	
Total pipe length	1.260	m
Nodes of the pipe	2	-
Wall material	Stainless Steel	-

- COMPONENT – LOWER LIQUID LINE

DESCRIPTION	VALUE	UNITS
Inner diameter of the pipe	0.002	m
External diameter of the pipe	0.003	
Total pipe length	0.774	m
Nodes of the pipe	2	-
Wall material	Stainless Steel	-

[OMISSIS]